Data Summary Report of Commercial Building Experiments in Salt Lake City, UT from May 17 to June 10, 2002

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EXECUTIVE SUMMARY

INTRODUCTION
Under some circumstances, it may be desirable to provide all or part of a building with collective-protection against harmful chemical or biological (CB) agents. Collective-protection, as opposed to individual protection, uses the building-- its architecture, ventilation system, and control components-- to safeguard the health of the building occupants in the event of an indoor or outdoor release of toxic agents.

In this study, we investigate the movement of tracer gases within a six-story building. The building was retrofitted to provide collective-protection on the upper two floors. To achieve this protection, the upper floors were over-pressurized using outside air that had passed through military specification carbon canisters and high-efficiency particulate air (HEPA) filters.

The four lower floors were outside the collective-protection area and had a ventilation system that was retrofitted to provide response modes in the event of a CB release. These response modes were designed to reduce the exposure of occupants on the lower floors without compromising the collective-protection zones. In this study, we also investigate the effectiveness of the ventilation system both during normal operation, and in its response modes.

Sixteen tests were performed between May 17 and June 10, 2002. These tests were designed to look at various aspects of building operation, such as collective-protection effectiveness, operation of the decontamination rooms, the effect of flush and shelter-in-place response modes for the lower floors, and the distribution of tracer gases within the fifth and sixth floors as a function of release location. This study is the first examination of a full-scale collective protection system retrofit in a commercial building. The results of these tests represent an unprecedented data set in terms of the spatial and temporal resolution of the data, in addition to the variety of release and operating conditions.

BUILDING SYSTEMS
Each of the protected floors included an elevator lobby, which was outside the protection envelope, and a two-chamber decontamination area between the lobby and the protected zones. The decontamination areas were designed to be used only during an actual chemical or biological incident.

The collective-protection system consisted of two identical air-handling units, mounted on the roof of the building. Each unit had a blower, a high-efficiency particulate air (HEPA) filter and a carbon canister filter that met military specifications. These systems supplied a constant flow of filtered air to the fifth and sixth floors, at a rate intended to maintain the upper floors at a positive pressure with respect to both the building exterior and the lower floors. The fifth and sixth floors were physically isolated from the rest of the building with 1) low-leakage pathway doors placed between the fourth and fifth

floors in each stairwell and 2) airlocks separating each of the upper floors from its respective elevator lobby.

Floors 1 to 4 of the building used a different ventilation system than the one that served the collective-protection areas and were provided with two ventilation system response modes: "flush" and "shelter-in-place".

DATA ANALYSIS AND RESULTS

The collective-protection system (CPS) was designed to maintain the upper two floors at a positive pressure with respect to the building exterior and the lower floors. Overall, when operated under design specifications, the CPS was able to maintain a positive pressure under the variety of meteorological conditions that occurred during the experimental period.

Under normal operating conditions, roughly half (52%) of the CPS floor air ex-filtrates through leakage pathways to the roof and the other half (48%) goes down to the fourth floor. However, the pressure difference between the sixth floor and the outside (13 Pa) was much greater than that between the fifth and fourth floors (4 Pa), which indicated that the leakage pathways to the lower floors were much larger than those to the roof.

The CPS filter system was transparent to the two tracers used. Since the building relief fans exhausted directly onto the CPS intakes, and the tracers were not removed by the CPS filters, the analysis of CPS effectiveness was significantly complicated by tracer transport through the CPS units. Efforts were made during the experiments to erect a physical barrier between the relief fan outlet and the CPS intakes; however, these efforts only succeeded in reducing, not eliminating, tracer entry into the CPS inlet.

Based on the pressure data collected, the CPS was effective at protecting the CPS floors from infiltration both from the exterior and from the lower floors. The effectiveness of the CPS assumes that the filtration system provides complete removal of the agent, without bypass or breakthrough. The effectiveness of the CPS filters was not tested in these experiments.

The ventilation system response modes for the lower floors of the building were tested using a release in the first floor lobby. Enabling the flush mode reduced both peak concentrations and total exposure.

Tests were also performed for a scenario in which the building was changed from normal operation to flush mode, based on the measured tracer signal at the location in the mechanical penthouse where the agent sensors had been located (i.e., simulating an agent signal). It took 12 minutes from the start of the release in the first floor main lobby for the tracer to reach the target trip-point in the penthouse. This substantial time delay results from the slow airspeeds in the return air flow path, through the first-floor ceiling plenum to the return shaft. Due to the relatively large cross-sectional area of the ceiling plenum, air speeds in the plenum are low, and return times are substantial. This supports

placement of agent sensors in key building areas (e.g. main and elevator lobbies) in addition to return plenums to reduce the 'time-to-detection'.

The shelter mode was effective at reducing air exchange rates for the lower four floors of the building, from approximately 1.2 air changes per hour (ACH) to approximately 0.3 ACH under the conditions of the test. Neither the flush nor the shelter mode compromised the CPS effectiveness based on differential pressure measurements between the CPS floors and the lower floors and outside.

Pressure and tracer tests were performed to assess the effectiveness of the decontamination rooms on the fifth and sixth floors, both with and without operation of the elevator shaft exhaust fan. During testing, the decontamination rooms on both floors were at negative pressure with respect to the elevator lobby. This will lead to agent migration from the elevator lobby into the first section of the decontamination room. Consequently, this zone may have high agent concentrations and be unsafe for removing protective clothing.

Since the second decontamination zone was held at a higher pressure than the first, tracer concentrations were substantially lower in the second decontamination zone and near or below the detection limit within the main collective protection areas. Use of the elevator exhaust fans reduced, but did not eliminate, the pressure difference and the consequent migration of tracer into the decontamination areas. This contamination of the decontamination areas could be eliminated by the use of variable-speed fans or dampers controlled by differential pressure sensors and programmed to ensure that proper pressure differences are maintained between the decontamination zones, the elevator lobbies, and protected areas.

I. Introduction

Under some circumstances, it may be desirable to provide all or part of a building with collective-protection against harmful chemical or biological (CB) agents. Collective-protection, as opposed to individual protection, uses the building-- its architecture, ventilation system, and control components-- to safeguard the health of the building occupants in the event of an indoor or outdoor release of toxic agents.

In this study, we investigate the movement of tracer gases within a six-story building. The building was retrofitted to provide collective-protection on the upper two floors. To achieve this protection, the upper floors were over-pressurized using outside air that had passed through military specification carbon canisters and high-efficiency particulate air (HEPA) filters.

The four lower floors were outside the collective-protection area and had a ventilation system that was retrofitted to provide response modes in the event of a CB release. These response modes were designed to reduce the exposure of occupants on the lower floors without compromising the collective-protection zones. In this study, we also investigate the effectiveness of the ventilation system both during normal operation, and in its response modes.

Sixteen tests were performed between May 17 and June 10, 2002. These tests were designed to look at various aspects of building operation, such as collective-protection effectiveness, operation of the decontamination rooms, the effect of flush and shelter-in-place response modes for the lower floors, and the distribution of tracer gases within the fifth and sixth floors as a function of release location. This study is the first examination of a full-scale collective protection system retrofit in a commercial building. The results of these tests represent an unprecedented data set in terms of the spatial and temporal resolution of the data, in addition to the variety of release and operating conditions.

II. Building Systems

As stated above, the top two floors of the building included a collective-protection system (CPS). Each of the protected floors included an elevator lobby, which was outside the protection envelope, and a two-chamber decontamination area between the lobby and the protected zones. The decontamination areas were designed to be used only during an actual chemical or biological incident.

The collective-protection system consisted of two identical air-handling units, mounted on the roof of the building. Each unit had a blower, a high-efficiency particulate air (HEPA) filter and a carbon canister filter that met military specifications (Figure 2.1). These systems supplied a constant flow of filtered air to the fifth and sixth floors, at a rate intended to maintain the upper floors at a positive pressure with respect to both the building exterior and the lower floors. Each of the CPS floors had a heating/cooling unit that conditioned and recirculated air on each floor. The CPS HVAC systems did not have relief fans; instead over-pressurization forced air through leakage pathways in the building shell.

Floors 1 to 4 of the building used a different ventilation system than the one that served the collective-protection areas (Figure 2.1). This design was intended to prevent the contamination of the protected areas with air recirculated from the lower floors. Although the lower floors were outside the collective-protection envelope, an effort was made to reduce the exposure of their occupants in the event of a CB release. To this end, the lower floors were provided with two ventilation system response modes: "flush" and "shelter-in-place". These response modes did not include any changes to the CPS ventilation system settings.

In case of an indoor release, a "flush" mode would have increased the flow of clean outside air to the lower floors, and simultaneously eliminated recirculation of contaminated air through the building's return air system by directing return air to outside. In the event of an outdoor release, a "shelter-in-place" mode would have shut down the building ventilation system and local exhaust fans, thereby minimizing the amount of outdoor air that entered the building. Either mode could have been activated with a single command from the building energy management system.

The instruments used to detect a CB attack were located in the heating, ventilating and air-conditioning (HVAC) penthouse on the roof, near the main HVAC system supply fans. Any sensor that measured a value over a particular threshold would have caused an alarm in the control room and led the operator to initiate an appropriate emergency response mode.

In normal operation, the ventilation system for the lower floors operated in a minimum outside air (MOA) mode with variable air volume (VAV) units on all floors set to "on-demand". Return air was drawn from the lower floors by the supply fans (recirculated back to the floors) and the relief fans (exhausted to the outside) located in the rooftop mechanical room penthouse.

While the building had separate ventilation systems for the protected and unprotected floors, the relief fans for the lower floors exhausted almost directly onto the collective-protection system's outside-air intakes. Thus, contaminant from an indoor release on the lower floors would have vented to the outside, then been drawn into the CPS. This was a potential problem when the building was in flush mode, and the large volume of air expelled by the relief fans may have prevented the effective dilution by clean outside air at the CPS intake.

Although the designer of the collective-protection system retrofit was aware of the problem of relief air from the lower floors "short-circuiting" into the CPS fresh air supply, for physical reasons there was no more suitable location for the CPS units. Nonetheless, it was important to keep in mind that this design required higher holding capacity for the carbon filters, in order to prevent breakthrough of recirculated contaminants.

The fifth and sixth floors were physically isolated from the rest of the building with 1) low-leakage pathway doors placed between the fourth and fifth floors in each stairwell and 2) airlocks separating each of the upper floors from its respective elevator lobby.
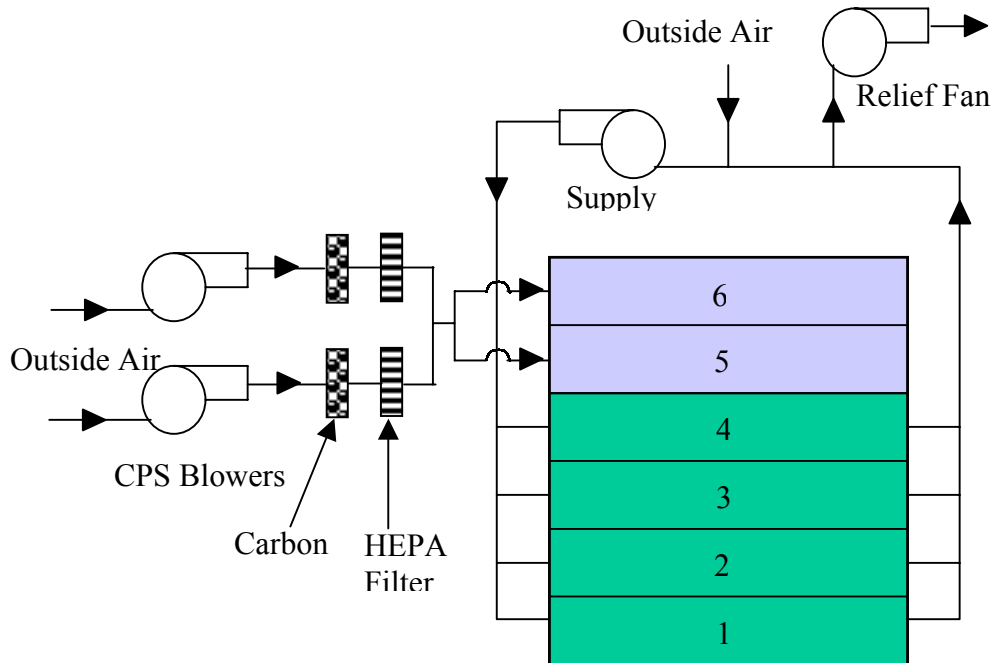

Figure 2.1. Schematic of major air handling systems in the building.

III. Methods

Building and room airflows were characterized with inert tracer gas measurements. Two tracer gases were used, propylene (C_3H_6) and sulfur hexafluoride (SF_6). Tracer gases were released in several locations throughout the building, and measurements made in multiple locations for each release scenario. In addition, differential pressure measurements at various locations and meteorological data were collected during each experiment. All experiments were conducted on weekend days when the building had few occupants, which enabled the research team to control use of doors and elevators.

REPLICATION

Many experiments were performed twice, in order to estimate the natural variability of the building system's performance. Replicates are identified by a letter appended to the main experiment number. For instance, Experiment 3 was run twice, as Experiments 3a and 3b. Building ventilation settings and tracer release locations were the same for replicates. However, outdoor meteorological conditions typically varied between replicates since they were perform at different times of day.

BUILDING VENTILATION CONTROLS

The CPS supply fans were operated at a constant design-specified speed for all experiments. During "in-use" building operations, the VAV damper settings would have varied based on the heating load in each zone. However, under the conditions of the experiments, most of the heat load (such as personnel and equipment) had been removed from the upper floors, leading to minimal airflow within the floors. To provide more typical and consistent airflows, the VAV units were set to their maximum set point for Experiments 4 through 16.

The ventilation system for the lower four floors, including all dampers, fans, and blowers, was computer-controlled by a system installed by Battelle Corp. As described above, the system provided two response scenarios to rapidly adjust fan and damper settings, depending on the source location (indoor or outdoor) of a detected airborne contaminant. In this study, normal HVAC operation modes, as well as the two response modes (building flush and shelter-in-place) were examined. Various fan and damper settings were used in the tracer gas experiments to quantify air movement between different regions of the building. The HVAC system for the lower four floors was equipped with a data logging program to record settings such as fan speeds and damper positions, however the data log proved to be unreliable for this study. Table 3.1 lists the HVAC mode, tracer release location, and objective of each tracer gas experiment.

During Experiments 8 through 16, plastic sheeting was placed between the exhaust from the lower floors and the intakes to the collective-protection system. The sheeting was intended to reduce the short-circuiting of tracer gas between the exhaust from the lower floors and the intakes for the protected floors.

PROPYLENE RELEASE SYSTEM

At the beginning of each experiment, C_3H_6 was released from a single location using a gas cylinder containing pure C_3H_6, a mass flow controller, a fan, a mixing tube, and a diffuser (Figure 3.1). In Experiments 3-6, C_3H_6 was released in the first floor West lobby (see Appendix A) at a target rate of 200 L min^{-1} for approximately 10 min. Due to the high flow rate, the internal temperature of the gas cylinder decreased, in turn decreasing the pressure inside the cylinder. To maintain a constant flow rate, the cylinder was placed in a warm water bath. Mass flow controller measurements were recorded during these high-flow-rate releases. The average flow rates are presented in Table 3.2.

In other experiments, C_3H_6 was released in locations on the fifth and sixth floors at a rate of 25 L min^{-1} for periods ranging from 5 to 20 minutes. In Experiment 1c, C_3H_6 measurements (described below) indicated that the initial C_3H_6 release did not create a sufficient peak concentration. As a result, a second release (1c2 in Table 2.2 was conducted at 40 L min^{-1}. C_3H_6 release start times, durations, and average flow rates are presented in Table 3.2 along with times that building flush mode was implemented at the end of certain experiments. The flush mode was used to ventilate C_3H_6 between many of the experimental runs. Exhaust dampers and doors for the collective protection floors

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were also opened between some of the runs to reduce the required flush time between experiments.

PROPYLENE SENSORS

C_3H_6 concentrations were measured and recorded at a rate of 50 Hz with Photo-Ionization Detectors (PID; Aurora Scientific, Inc.; Aurora, Ontario, Canada). The PID dimensions were 5 cm high, 7.5 cm wide, and 22 cm long (Figure 3.2). Each sensor sampled continuously at a flow rate of 800 SCCM and had a limit of detection to C_3H_6 in air of about 40 ppb. In the PID, a gas sample was exposed to ultraviolet (UV) light that ionized molecules with ionization energy levels below the UV lamp energy (10.6 eV). Ions were collected on positive and negative electrodes creating a current proportional to the gas concentration.

The quantities of C_3H_6 released in each experiment produced concentrations far greater than those of other species present with ionization potentials below 10.6 eV. This was confirmed with background measurements made between each experiment, and by measurements of outdoor air made during each experiment.

Up to 30 PIDs were placed throughout the building for each experiment. Each PID was serially connected to two centrally located data-logging computers. Measurements from each PID were logged at a rate of 50 Hz. Each 50 Hz data log of analog/digital units (adu) was processed by first subtracting the baseline value recorded at the start of the run and then scaling by the appropriate quadratic calibration factors (described below) to yield the C_3H_6 concentration.

The temperature at each PID location was recorded every two minutes with a data logging sensor (Onset Computer Corp; Bourne, MA; model HOBO). Floor plans indicating the location of each PID in each experiment are shown in Appendix A.

SULFUR HEXAFLUORIDE (SF_6) RELEASE SYSTEM

In Experiment 1b, SF_6 was released using a gas cylinder of pure SF_6, a flow meter (Bios, Inc; Butler, NJ), and polypropylene tubing. SF_6 releases in Experiments 3, 4, and 6 were performed by pumping out tedlar bags containing known amounts of SF_6. The tedlar bags were filled from gas cylinders of pure SF_6 via a flow meter. SF_6 release locations, start times, release durations, and release volumes are presented in Table 3.3.

SF_6 MEASUREMENTS

Automated programmable bag samplers, designed by LBNL and known as "blue boxes," were used to collect grab samples in tedlar bags during Experiments 3, 4, and 6. Each blue box was programmed to fill six separate polyethylene-lined bags (Calibrated Instruments, Inc.; Hawthorne, NY) with approximately 200 cm^3 of sample air (at ~25 cm^3 sec^{-1}) at elapsed times of 10, 15, 20, 30, 45, and 60 min after the SF_6 release. To establish background concentrations, one bag in each blue box was filled before each SF_6 release. In some experiments, an eighth bag was filled 60 min after the seventh bag. Temperature data at each blue box location was recorded every two minutes with a data

logging sensor (Onset Computer Corp; Bourne, MA; model HOBO). Blue box locations are shown in the floor plans in Appendix A.

Bag samples were returned to Lawrence Berkeley National Laboratory (LBNL) and analyzed for SF_6 and C_3H_6 using both gas chromatograph/electron capture detector (GC/ECD; Hewlett Packard; Palo Alto, CA; Model 5890A) and quadrupole mass spectrometry (MS; Balzers; East Syracuse, NY; model Quadstar). GC/ECD measurements were used for bags with SF_6 concentrations <700 ppb and MS measurements were used for bags >700 ppb.

HVAC FLOW RATE MEASUREMENTS

Tracer gas techniques were used to determine flow rates throughout the HVAC system by releasing SF_6 from a gas cylinder via a mass flow controller into a particular duct section. Downstream of the injection location, the SF_6 concentration was measured with an infrared spectrophotometric detector (Thermo Environmental Instruments, Franklin, MA; MIRAN SapphIRe 205B Series). Distances between injection and detection points were selected to maximize mixing time. With the assumption of complete mixing, the flow rate Q was determined with

$$Q = \frac{E}{C}$$ (3.1)

where E is the SF_6 injection flow rate and C is the downstream SF_6 concentration.

DIFFERENTIAL PRESSURE MEASUREMENTS

The direction and flow rate of air through building interfaces (e.g. exterior doors, interior doors, windows, cracks, etc.) depends on pressure difference across the interface. Differential pressure measurements were made with multi-channel pressure sensors (Energy Conservatory, Minneapolis, MN; model APT 8) and recorded every 20 sec during Experiments 1-8 and 10-16, and every 1 sec for Experiment 9.

Differential pressures were measured between the first floor main lobby and 1) outside the building's main first floor entrance, 2) inside the stairwell to the basement parking garage, and 3) in an interior first floor room. Measurements were also made between the sixth floor hallway and 1) the East stairwell on the first floor, 2) the East stairwell on sixth floor, 3-6) the main hallways of the second to fifth floors, 7) the fourth floor side of a stairwell door between the fourth and fifth floors, and 8) outside on a balcony on the sixth floor. Differential pressure measurements were also made between a sixth floor office and 1) the outside, 2-4) the main hallways of the fourth to sixth floors, 5) the sixth floor West stairwell, 6) the sixth floor elevator lobby, and the 7) fifth floor airlock.

METEOROLOGICAL DATA

During each tracer gas experiment, measurements of temperature, relative humidity, barometric pressure, wind speed, and wind direction were recorded every 10 seconds on the roof of the building and every hour at the Salt Lake City International Airport located 7 km West of the building.

TRACER MEASUREMENT CALIBRATIONS

Each PID was calibrated with 0, 10, 100, and 1000 ppm of C_3H_6 in air from compressed gas cylinders (Scott Specialty Gases, San Bernardino, CA; Sure Class grade, ±5%) both before and after each weekend of experiments. The mean-absolute error of the calibrated response with respect to the actual calibration concentration ranged from 0.5 to 5.5 ppm (μ=2.2 ppm, σ=1.1 ppm) for the 31 PIDs used.

The GC/ECD and MS instruments were calibrated with known amounts of SF_6 and C_3H_6 from polyethylene-lined bags. Since it was not possible to immediately analyze the bag samples with GC/ECD and MS, potential reaction or surface losses of SF_6 and C_3H_6 were evaluated using samples bags filled with known concentrations of SF_6 and C_3H_6 at the building site. GC/ECD and MS measurements of these field "calibration" bags indicated no losses of SF_6 and C_3H_6 during the time between performing the experiments and analyzing the sample bags.

ELECTRONIC COPIES OF ALL DATA

Copies of all tracer concentration, differential pressure, interior temperature, and outdoor meteorological measurements are provided in text file format. The PID data text files have been compressed into zip files. PID data files designated "5b" contain data for both Experiments 5b and 6a because the data logging computers were not re-set between these runs. All instrument layout maps are provided in pdf format. A list of all folder, data files, and floor maps are provided in Appendix B.

Figure 3.1. Propylene injection system with propylene cylinder shown in front of fan, mixing tube, diffuser, and mass flow controller.
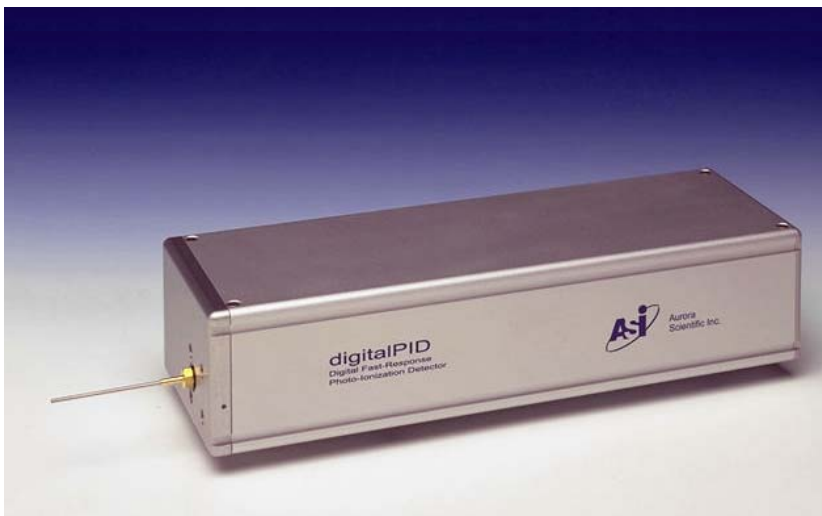
Figure 3.2. Photo-Ionization Detector (PID). Small-diameter tube on the left side is sample inlet port.

Table 3.1. Tracer gas experiment release locations, building ventilation settings, and objectives.

Exp	C_3H_6 Release Location[1]	Building Ventilation Settings	Objective[2]
1a	Flr 5 Conf Rm	Flrs 1-4: supply 100%, relief 50%. Flrs 1-6: VAV on-demand. Elevator exh fan on. Flrs 5-6: dmprs closed.	Systems test of all sensors and datalogging equipment
1b	Flr 5 Conf Rm	Same as above.	Test how conservative propylene is as a tracer. Determine repeatability by releasing propylene and SF_6 in the same location.
1c, 1d	Flr 5 Conf Rm	Same as above.	Determine repeatability.
2	Flr 5 Hall	Same as above.	Investigate effect of source location by comparing to Experiment 1
3a, 3b	Flr 1 Lobby	Same as above except relief fans off.	SF_6 released in floors 1-4 intake. Test collective protection. Quantify airflow from floors 1 thru 4 to floors 5 and 6 in flush mode.
4a, 4b	Flr 1 Lobby	Flush mode (100% outside air, supply 50%, relief 100%. Flrs 5–6: dampers closed).	SF_6 released in floors 1-4 intake. Determine effectiveness of building flush protocol. Quantify airflow from floors 1 thru 4 to floors 5 and 6 in flush mode.
5a, 5b	Flr 1 Lobby	Triggered flush mode (same as above, but switched from normal operation on trigger set point).	Determine response time for triggered flush mode. Quantify airflow from floors 1 thru 4 to floors 5 and 6 in flush mode.
6a, 6b	Flr 1 Lobby	Shelter mode (20% outside air, supply off, relief off).	SF_6 released in floors 1-4 intake. Determine building airflows and Quantify airflow from floors 1 thru 4 to floors 5 and 6 in flush mode.
7a, 7c[3]	Flr 5 Elev Lobby	Flrs 1-4: 100% recirculation.	Test collective protection for floor 5 elevator lobby contamination.
8	Flr 5 Elev Lobby	Flrs 1-4: 100% recirculation, supply 15%, relief off. Flrs 1-6: VAV max. Elevator exhaust fan on.	Test collective protection for floor 5 elevator lobby contamination. Test effect of elevator exhaust fan on contaminant migration into decontamination area and other floors.
9	Flr 5 Elev Lobby	Flrs 1-4: 100% recirculation, supply 15%, relief off. Flrs 1-6: VAV max. Elevator exhaust fan off.	Test collective protection for floor 5 elevator lobby contamination. Test effect of elevator operation on contaminant migration into decontamination area and other floors.
10a, 10b	Flr 5 Conf Rm	Flrs 1-4: 100% recirculation, supply 15%, relief off. Flrs 1-6: VAV max.	Investigate effect of VAV settings on tracer gas results
11	Flr 6 Elev Lobby	Flrs 1-4: 100% recirculation, supply 15%, relief off. Flrs 1-6 VAV max. Decon fan on. Elevator fan off.	Test collective protection for floor 6 elevator lobby contamination.
12	Flr 6 Elev Lobby	Flrs 1-4: 100% recirculation, supply 15%, relief off. Flrs 1-6: VAV max. Decon fan on. Elevator fan on.	Test collective protection for floor 6 elevator lobby contamination. Test effect of elevator exhaust fan on contaminant migration into decon area and other floors.
13	Flr 5 Mech Rm	Flrs 1-4: no recirculation, supply 15%, relief 30%. Flrs 1-6: VAV max. Elevator fan off.	Determine how much air from floor 5 goes to floors 1 thru 4. Investigate distribution of floor 5 HVAC system.
14	Flr 5 Mech Rm	Flrs 1-4: no recirculation, supply 15%, relief 50%. Flrs 1-6: VAV max. Elevator fan off.	Determine how much air from floor 5 goes to floors 1 thru 4. Investigate distribution of floor 5 HVAC system.
15	Flr 5 Hall	Flrs 1-4: no recirculation, supply 43%, relief 50%. Flrs 1-6: VAV max. Elevator fan on.	Majority of sensors on floor 5. Investigate effect of source location. Provide data for sensor analysis model.
16	Flr 5 Hall	Same as above	Majority of sensors on flr 5. Test model prediction of source location.

1. See maps in Appendix A.
2. Objectives in addition to providing data for model/prediction comparison.
3. Exp 7b was aborted due to a computer failure. It was re-run as exp 7c.

Table 3.2. Propylene release start times, durations, and average flow rates. Also, building flush mode start times.

Exp	PID Start Date and Time	Propylene Release			Flush Start Date and Time
		Start Time	Duration (sec)	Avg Flow Rate (L min^{-1})	
1a[1]	NA	03:45	300	25	NA
1b	5/18/02 21:50	22:02	3	25	NA
1c	5/19/02 00:10	00:20	300	25	NA
1c2	5/19/02 00:10	01:17	600	40	NA
1d	5/19/02 07:35	07:40	1200	25	5/19/02 12:05
2	5/19/02 14:05	14:27	1650	25	5/19/02 18:15
3a	5/25/02 11:40	11:43	600	180	5/25/02 14:44
3b	5/25/02 17:20	17:32	1440	160	5/25/02 21:41
4a	5/25/02 23:40	23:50	600	200	NA
4b	5/26/02 07:50	08:00	660	147	NA
5a	5/26/02 16:20	16:35	600[1]	~200[2]	5/26/02 16:49
5b	5/26/02 21:25	21:31	600[1]	~200[2]	5/26/02 21:50
6a	5/26/02 21:25	23:50	300	200	5/27/02 06:01
6b	5/27/02 08:50	09:00	480	126	5/27/02 14:05
7a	6/01/02 01:25	01:35	600	25	6/01/02 06:00
7c	6/01/02 11:40	12:30	600	25	6/01/02 14:34
8	6/01/02 16:10	16:20	600	25	NA
9	6/01/02 19:30	19:40	600	25	NA
10a	6/01/02 23:40	00:00	1200	25	6/02/02 07:15
10b	6/02/02 08:30	09:00	1200	25	6/02/02 13:40
11	6/07/02 22:06	22:45	600	25	NA
12	6/08/02 06:50	07:00	600	25	6/08/02 10:27
13	6/08/02 11:30	11:39	900	25	NA
14	6/08/02 17:55	18:02	1200	25	NA
15	6/09/02 02:10	02:15	600	25	NA
16	6/09/02 06:50	07:00	600	25	NA

1. Systems test to trouble shoot sensors and data logging equipment
2. Approximate values due to flow control problems.

Table 3.3. SF$_6$ release locations, start times, durations, and volumes.

Exp	Location	Start Date and Time	Duration (sec)	Volume (L)
3a	Floor 1-4 Intakes	05/25/02 11:37	580	383
3b	Floor 1-4 Intakes	05/25/02 17:30	2160	357
4a	Floor 1-4 Intakes	05/25/02 23:50	~800[1]	375
4b	Floor 1-4 Intakes	05/26/02 08:00	705	370
6a	Floor 5 Mech Room	05/26/02 23:50	540	101
6b	Floor 5 Mech Room	05/27/02 09:00	300	100

1. Exact time was not noted at time of experiment.

IV. Data Analysis and Results

Experiment 1b was conducted to confirm that propylene would be a conservative tracer in the building. Propylene and SF_6 were released simultaneously in the fifth floor conference room. Concentrations measured by two pairs of co-located PIDs and MIRANs in the conference room show near identical decay rates (Figure 4.1). The air exchange rates measured by each tracer decay were within 2%, indicating that propylene was as conservative a tracer as SF_6.

As described above, the collective-protection system (CPS) was designed to maintain the upper two floors at a positive pressure with respect to the building exterior and the lower floors. Figure 4.2 shows a typical differential pressure trace. The figure shows that the CPS was effective at keeping the sixth floor at a higher pressure than the fourth floor. To rapidly remove tracer gas from the building between experiments, the building's EMS system was overrode and fan speeds were set outside the system design specifications. During some of these periods the CPS floors were at a lower pressure than floors 1-4 and the outside. Overall, when operated under design specifications, the CPS was able to maintain a positive pressure under the variety of meteorological conditions that occurred during the experimental period.

As described in the Building Systems section above, the CPS floors were not equipped with relief fans to remove ventilation air. The only exhaust pathways for the filtered air being supplied to the CPS floors was via bathroom and decon room exhausts and through leakage pathways either to the exterior or to areas of the building outside of the CPS. The relative leakage to the interior and exterior can be determined by assuming the primary leakage pathways were cracks and calculating the flow through the cracks using

$$Q = C\Delta P^n \qquad (4.1)$$

where ΔP was the pressure difference across the pathway (Thatcher et al., 2001). The coefficient C and the exponent n were determined from non-linear curve-fits generated from flow and pressure difference data acquired from several different settings of the HVAC fans serving the lower floors.

Under normal operating conditions, roughly half (52%) of the CPS floor air ex-filtrates through leakage pathways to the roof and the other half (48%) goes down to the fourth floor. However, the ΔP between the sixth floor and the outside (13 Pa) was much greater than the ΔP between the fifth and fourth floors (4 Pa) which indicated that the leakage pathways to the lower floors were much larger than those to the roof.

Fan flow rates measured by SF_6 are shown in Table 4.1. All fan flow measurements were made during the last two weekends of experiments at times when the ventilation systems were operating in MOA mode and VAV units were set to maximum flow. Replicates of fan flow measurements agreed with each other within 3%.

The CPS filter system was transparent to the two tracers used. Since the building relief fans exhausted directly onto the CPS intakes, and the tracers were not removed by the

CPS filters, the analysis of CPS effectiveness was significantly complicated by tracer transport through the CPS units. Efforts were made during the experiments to erect a physical barrier between the relief fan outlet and the CPS intakes; however, these efforts only succeeded in reducing, not eliminating, tracer entry into the CPS inlet.

Based on the pressure data collected, the CPS was effective at protecting the CPS floors from infiltration both from the exterior and from the lower floors. The effectiveness of the CPS assumes that the filtration system provides complete removal of the agent, without bypass or breakthrough. The effectiveness of the CPS filters was not tested in these experiments.

The ventilation system response modes for the lower floors of the building were tested using a release in the first floor lobby. Figure 4.3 compares representative sensor responses for releases under typical HVAC operating conditions and under flush mode operation. Enabling the flush mode reduced both peak concentrations and total exposure.

Tests were also performed for a scenario in which the building was changed from normal operation to flush mode, based on the measured tracer signal at the location in the mechanical penthouse where the agent sensors had been located (i.e., simulating an agent signal). Figure 4.4 shows that it took 12 minutes from the start of the release in the first floor main lobby for the tracer to reach the target trip-point in the penthouse. This substantial time delay results from the slow airspeeds in the return air flow path, through the first-floor ceiling plenum to the return shaft. Due to the relatively large cross-sectional area of the ceiling plenum, air speeds in the plenum are low, and return times are substantial. This supports placement of agent sensors in key building areas (e.g. main and elevator lobbies) in addition to return plenums to reduce the 'time-to-detection'.

Figure 4.5 compares representative building responses for releases under typical HVAC operating conditions and under shelter mode operation. Air exchange rates were calculated using the tracer gas decay method (ASHRAE, 1997). The shelter mode was effective at reducing air exchange rates for the lower four floors of the building, from approximately 1.2 air changes per hour (ACH) to approximately 0.3 ACH under the conditions of the test. Neither the flush nor the shelter mode compromised the CPS effectiveness based on differential pressure measurements between the CPS floors and the lower floors and outside.

Pressure and tracer tests were performed to assess the effectiveness of the decontamination rooms on the fifth and sixth floors, both with and without operation of the elevator shaft exhaust fan. During testing, the decontamination rooms on both floors were at negative pressure with respect to the elevator lobby. This will lead to agent migration from the elevator lobby into the first section of the decontamination room. Consequently, this zone may have high agent concentrations and be unsafe for removing protective clothing.

Since the second decontamination zone was held at a higher pressure than the first, tracer concentrations were substantially lower in the second decontamination zone and near or

below the detection limit within the main collective protection areas. Figure 4.6 shows the C_3H_6 concentrations in the fifth floor elevator lobby and the two decontamination zones for a fifth floor elevator lobby release. Use of the elevator exhaust fans reduced, but did not eliminate, the pressure difference and the consequent migration of tracer into the decontamination areas. This contamination of the decontamination areas could be eliminated by the use of variable-speed fans or dampers controlled by differential pressure sensors and programmed to ensure that proper pressure differences are maintained between the decontamination zones, the elevator lobbies, and protected areas.

V. Summary
Over the course of four weeks, 16 tracer gas experiments were conducted in a commercial building that had been modified to protect occupants in the event of a CB release. Tracer gas concentrations were measured at a rate of 50 Hz in up to 30 locations in each experiment, which provided data with very high spatial and temporal resolution. Differential pressure and temperature measurements were also made throughout the building.

Experiments showed that the CPS maintained a positive pressure differential between the upper two floors and the lower floors with various meteorological conditions and within specified settings of the HVAC fans serving the lower floors. Tracer gas analysis of the efficacy of the CPS was hampered by 1) the discharge of relief air from the lower floors directly into the CPS intakes and 2) the lack of removal of the tracer gases by the CPS carbon filters. Future work will use simulation tools to further analyze the performance of the CPS. The tracer experiments did show that a CB agent could enter the first zone of the decontamination areas on each CPS floor. This should be addressed with variable speed exhaust fans in future designs.

Tracer gas analysis showed that the shelter in place HVAC mode provided protection of lower floor occupants from an outdoor release by significantly lowering the air exchange rates on those floors. It was also determined that the efficacy of a flush mode triggered by an agent sensor depends greatly on the location of the sensor. Future work will further analyze the tracer gas data to quantify airflow and pollutant transport within and between floors of the building.

References
ASHRAE (1997) ASHRAE Handbook: Fundamentals. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA.

Thatcher T.L., McKone T.E., Fisk W.J., Sohn M.D., Delp W.W., Sextro R.G. (2001) Factors affecting the concentration of outdoor particles indoors (COPI): Identification of data needs and existing data. Lawrence Berkeley National Laboratory Report, LBNL-49321, Berkeley, CA.
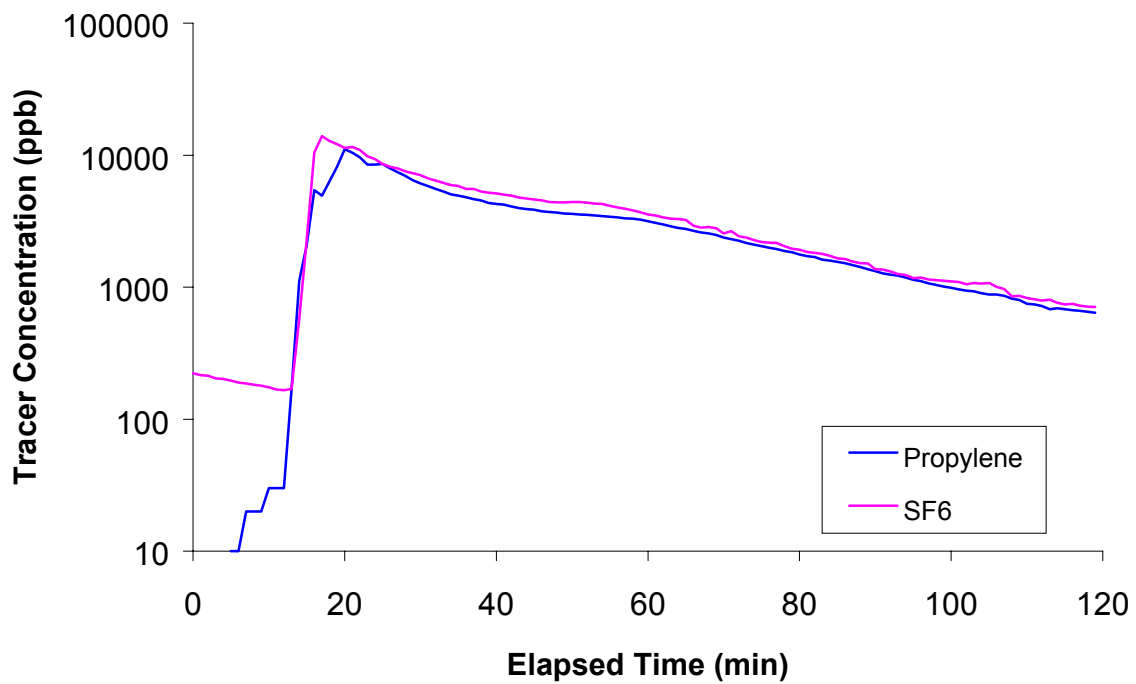
Figure 4.1. Comparison of propylene and SF_6 decay indicating the two tracers are comparably conservative in the building.
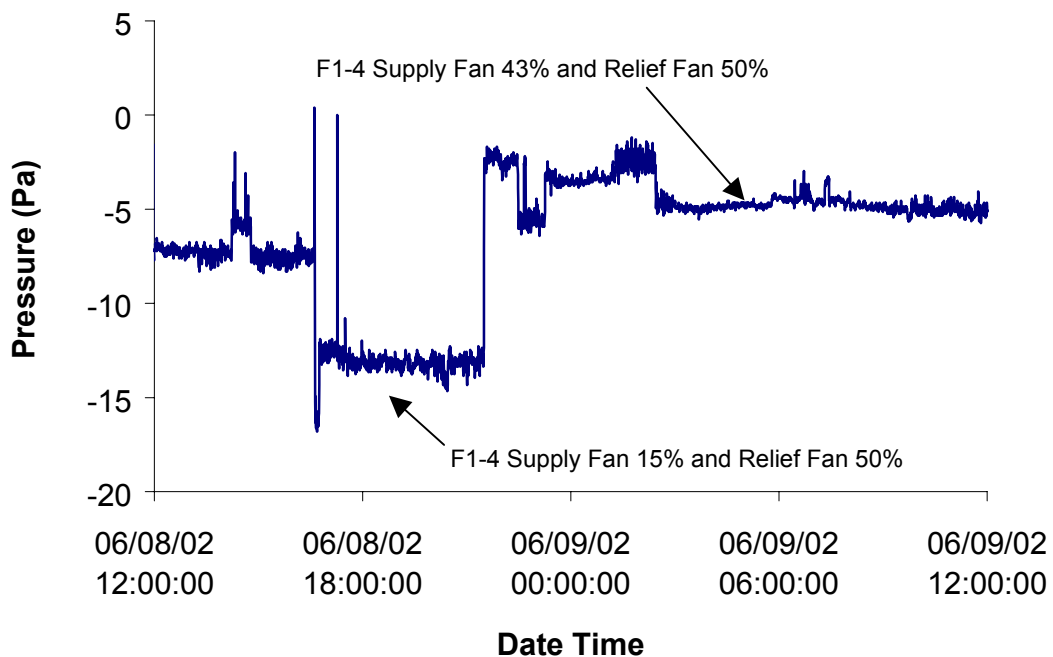
Figure 4.2. Differential pressure measurement of the 4th floor relative to the 6th floor during experiments 13-16.

14
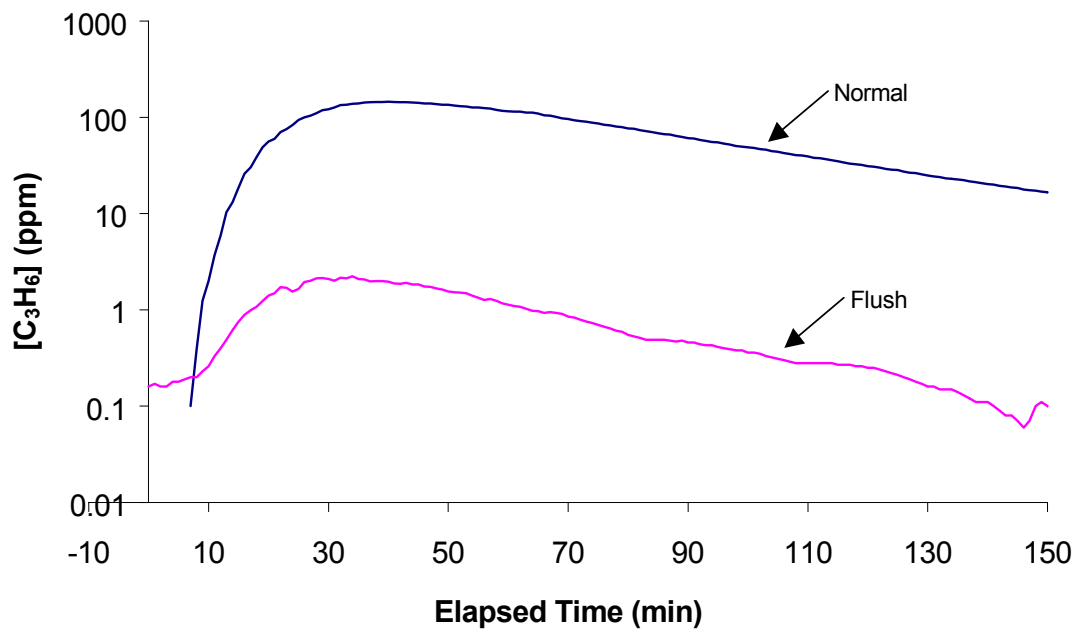
Figure 4.3. Comparison of tracer concentration in a first floor office during normal and flush HVAC operation with a first floor lobby release.
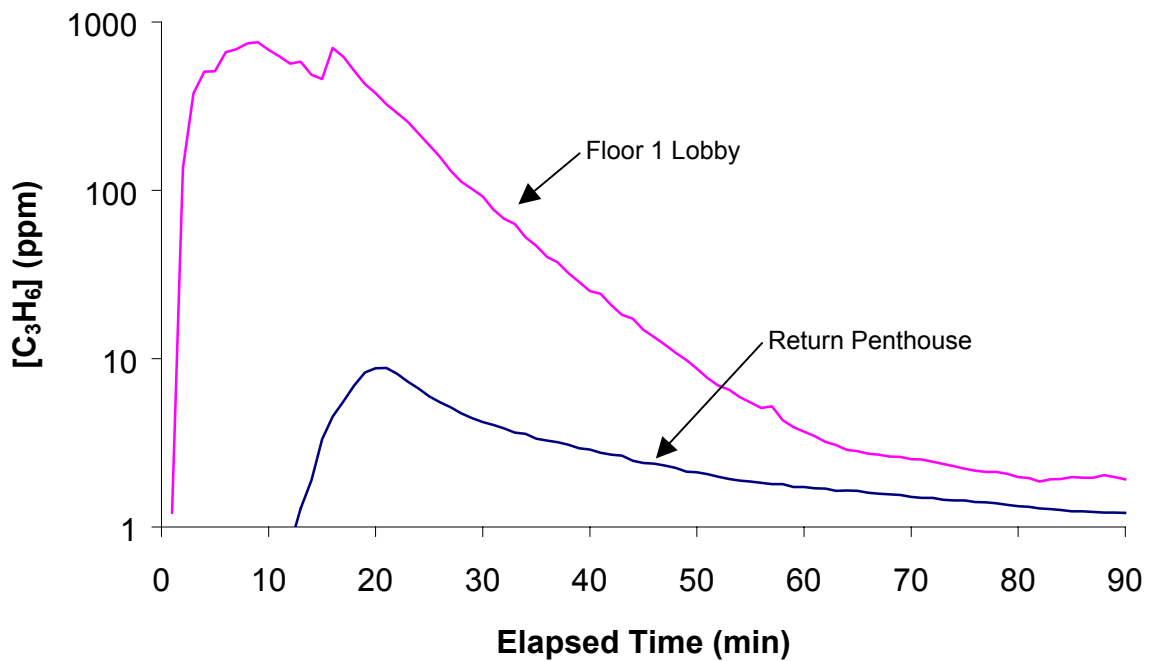
Figure 4.4. Tracer concentration in penthouse return for release on the first floor at time zero and triggered flush HVAC operation.
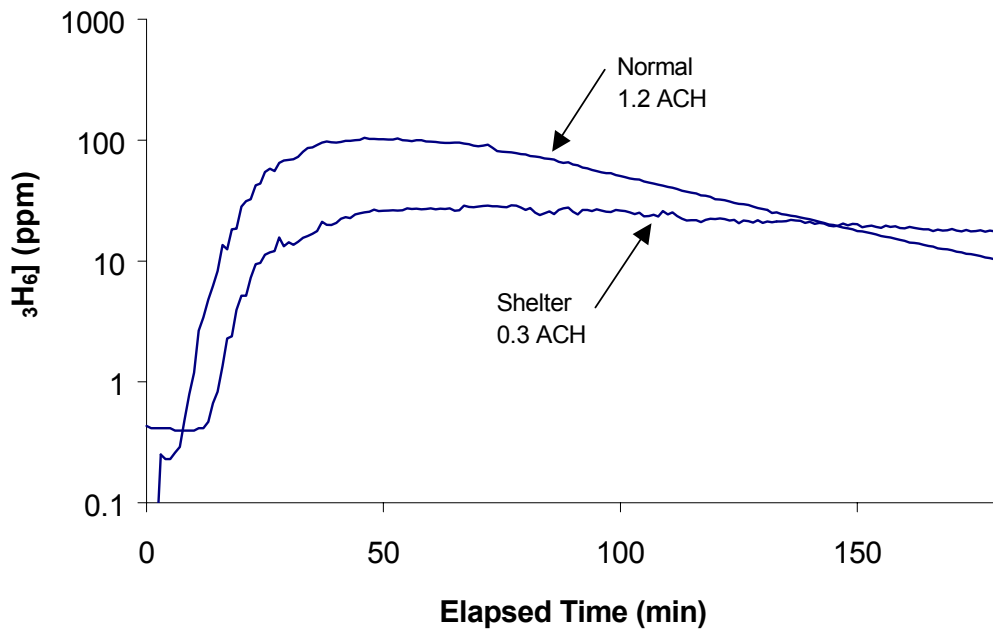
Figure 4.5. Comparison of tracer concentration in a first floor office during normal and shelter HVAC operation with a first floor lobby release.
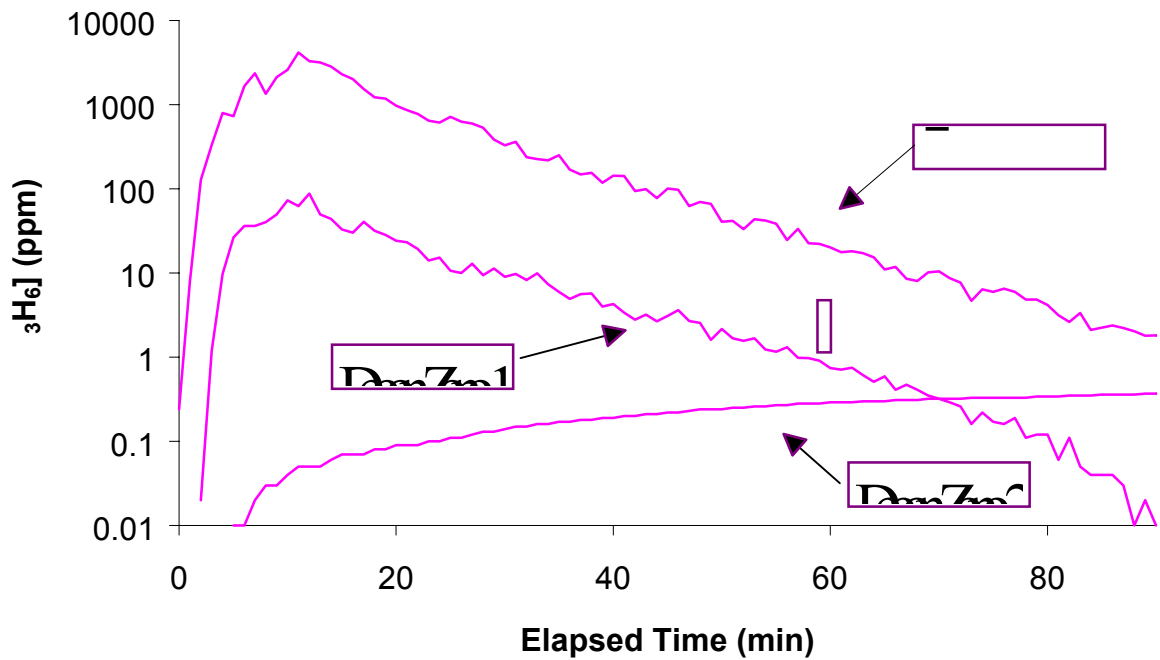
Figure 4.6. Tracer concentration in the release location (fifth floor elevator lobby) and both fifth floor decontamination zones.

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Table 4.1. Fan flow rate measurements made with SF_6.

Fan	SF_6 Injection Rate (mL min^{-1})	[SF_6] (ppb)	Flow Rate (ft^3 min^{-1})
East CPS Blower	406	1291	10600
East CPS Blower	406	1369	10900
Floors 1-4 Supply[1]	3585	1341	93900
Floors 1-4 Supply[1]	3578	1381	92900
Floors 1-4 Supply[2]	3580	2272	56500
Floors 1-4 Supply[3]	3575	2388	53700
Floors 1-4 Supply[4]	3565	2721	47000
Floors 1-4 Return[1]	3817	1766	77500
Floors 1-4 Return[2]	3832	2047	67100
Floors 1-4 Return[3]	3823	2644	51800
Floors 1-4 Return[4]	3832	6143	22400
Elevator Exhaust	364	979	13300
Elevator Exhaust	363	989	13200
Floor 5 and 6 Decon	164	2255	2600
Bathroom Exhaust	163	911	6400

1. Fan settings: supply 43% and relief 50%.
2. Fan settings: supply 15% and relief 50%.
3. Fan settings: supply 15% and relief 30%.
4. Fan settings: supply 15% and relief off (100% recirculation).

Appendix A: Instrument layout floor maps for all experiments conducted from May 17 to June 10, 2002

Appendix A Legend:

     Propylene Release Location

     Photoionization Detector (PID) Location

     Automated Bag Sample Collector (Blue Box) Location

     MIRAN Sampler Location

Below each floor map is a list of each PID on that floor along with its corresponding temperature sensor datalogger.

Experiments 1 and 2: Sat 5/18/02- Sun 5/19/02

40- HOBO SH04

1st Floor

A-3
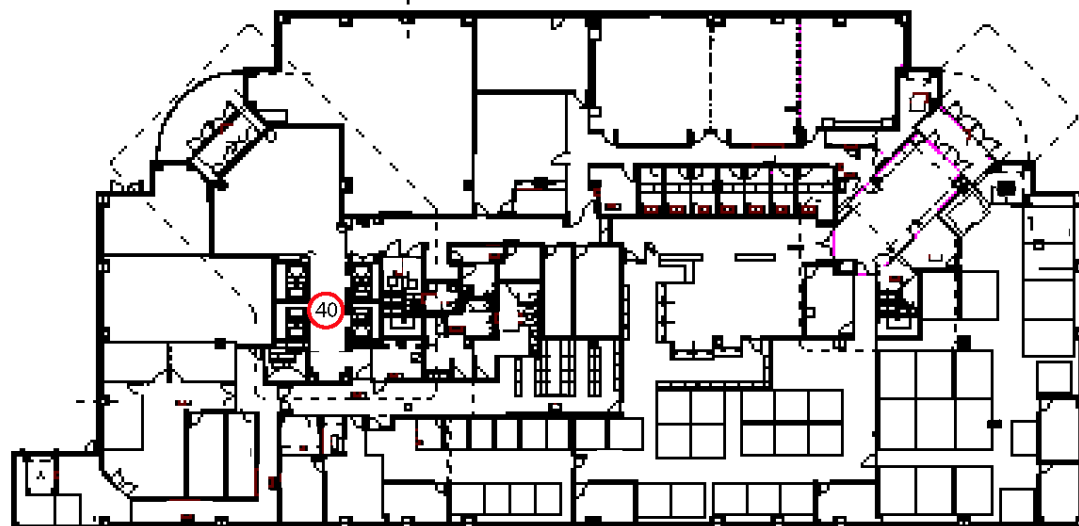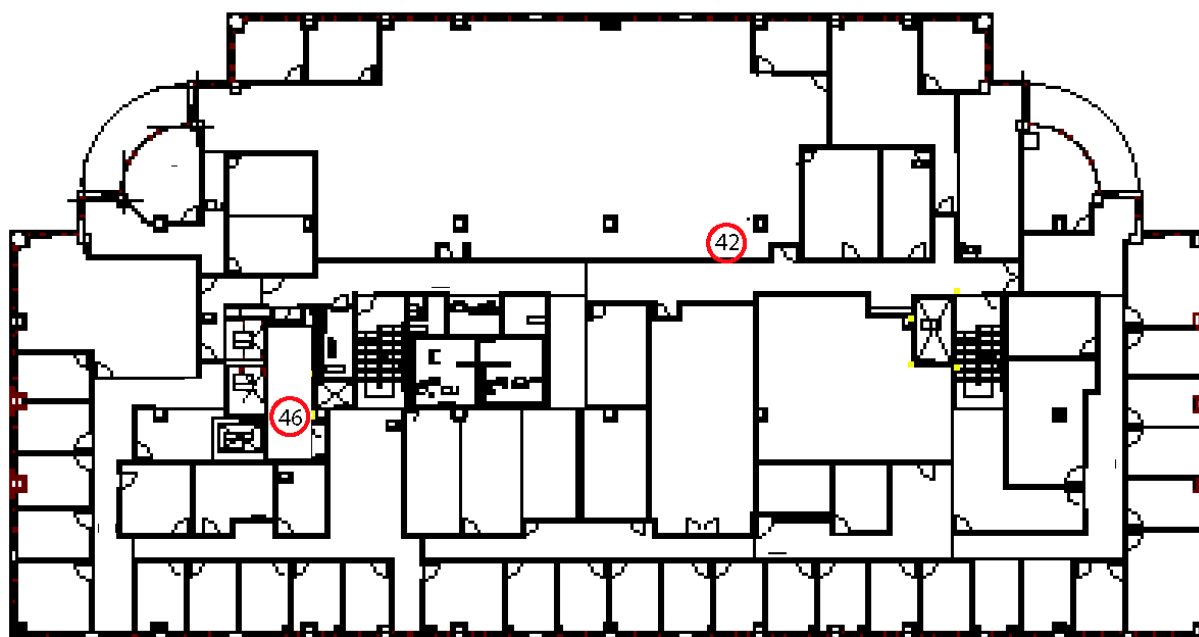
Experiments 1 and 2: Sat 5/18/02- Sun 5/19/02

39-HOBO SH11

2nd Floor

A-4

Experiments 1 and 2: Sat 5/18/02- Sun 5/19/02

46-HOBO SH22
42-HOBO SH05 (ceiling plenum)

3rd Floor

Experiments 1 and 2: Sat 5/18/02- Sun 5/19/02
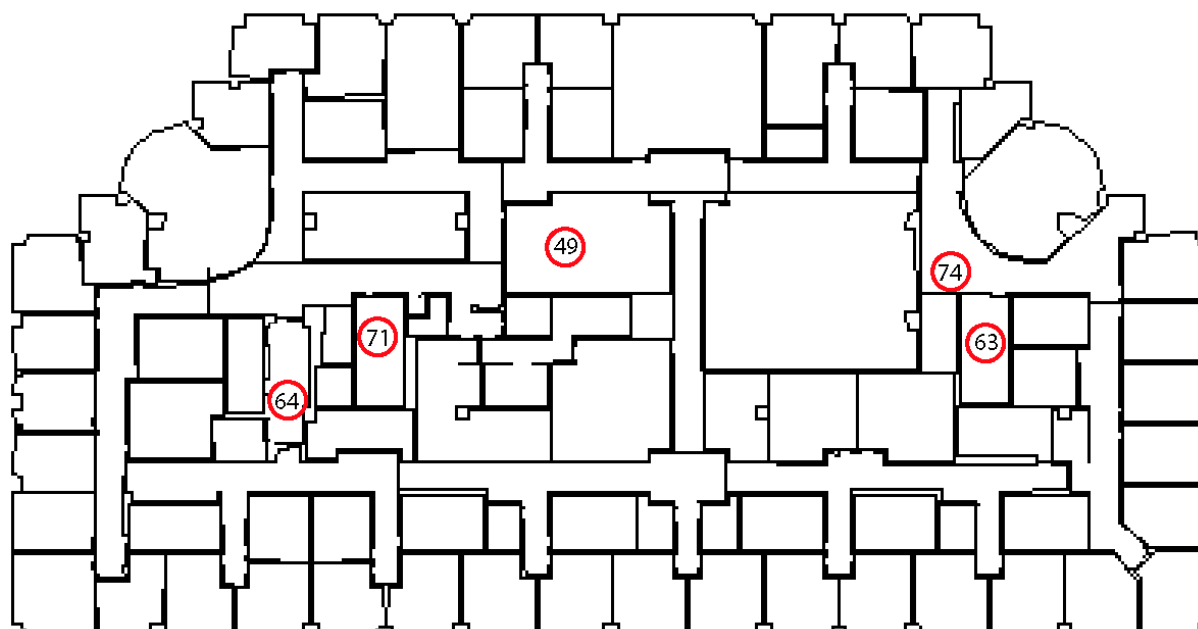
4th Floor

64-HOBO SH21
71- HOBO SH10
49- HOBO SH13
74- HOBO SH07 (ceiling return)
63- HOBO SH12

Experiment 1: Sat 5/18/02- Sun 5/19/02
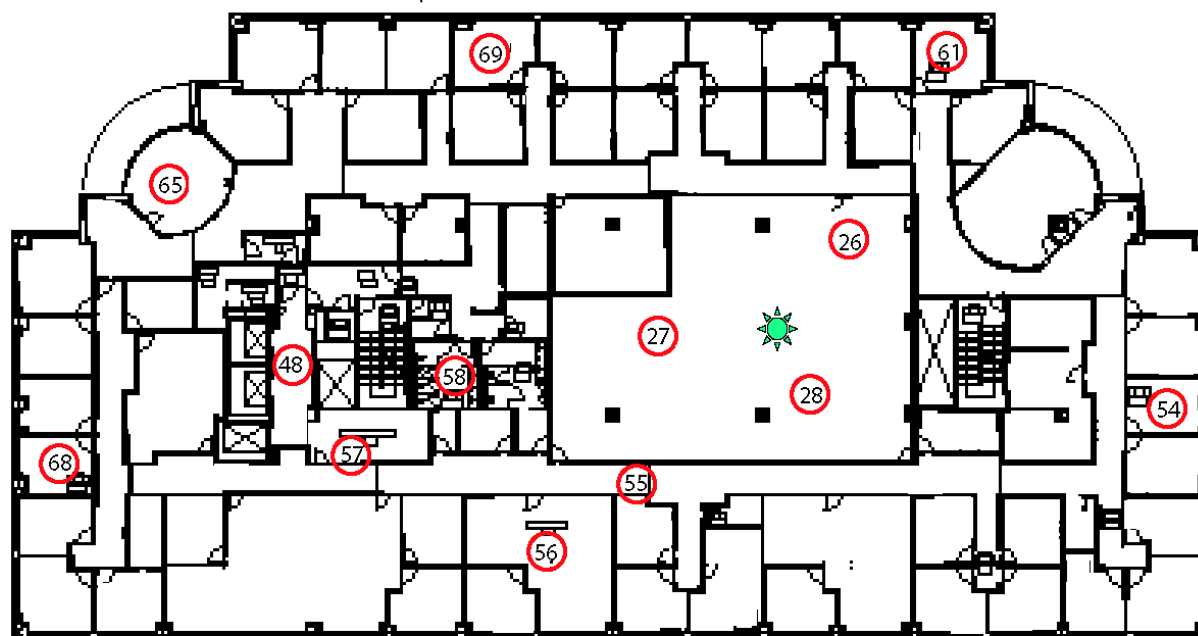
5th Floor

61-HOBO SH08
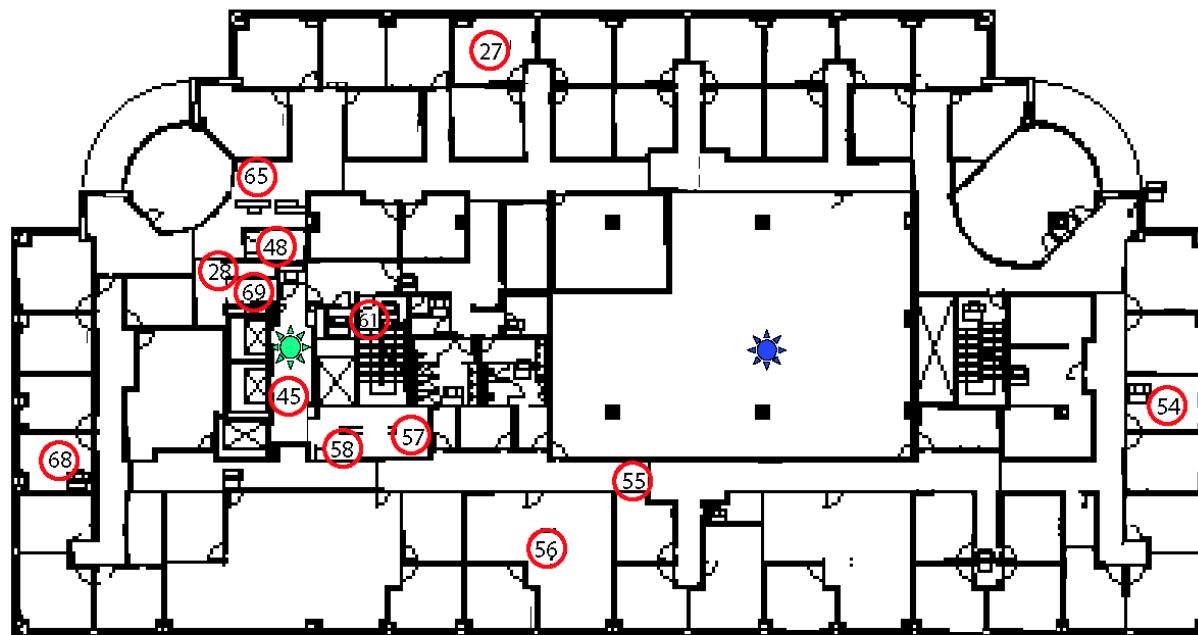26-HOBO SH16
28-HOBO SH14
27-HOBO SH09
69-HOBO SH20
65-HOBO SH02
68-HOBO SH19

54-HOBO SH23
55-HOBO SH17
56- HOBO SH25
58-no HOBO
57-HOBO SH26
48-no HOBO

Propylene Release Location for
Experiment 1

Experiment 2: Sun 5/19/02
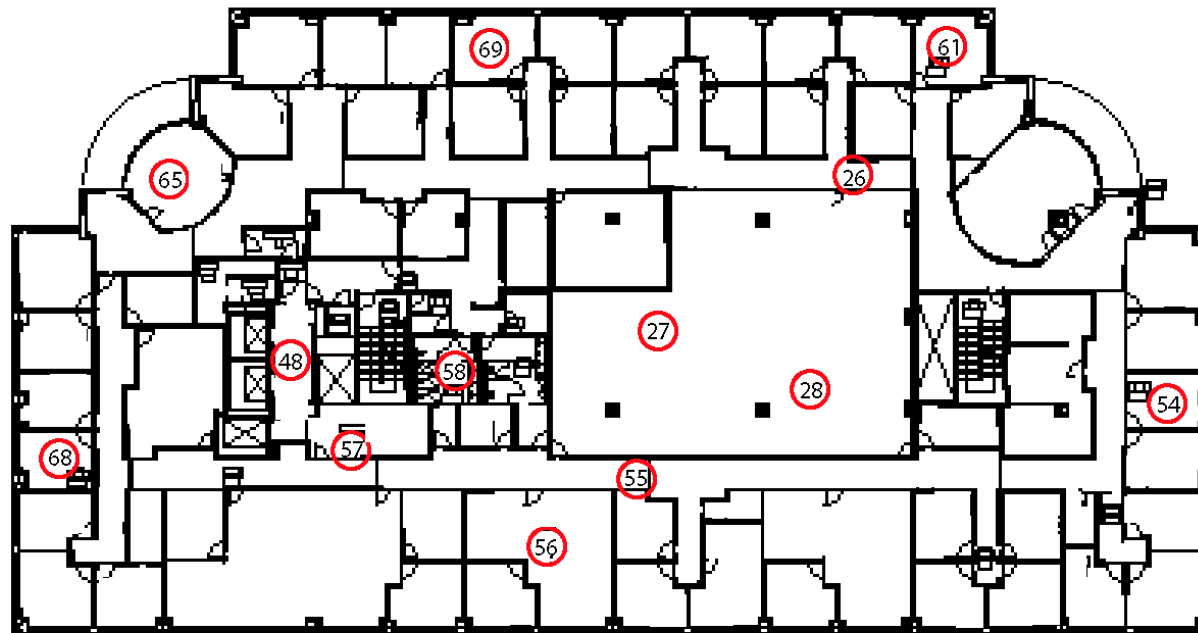
5th Floor

61-HOBO SH08
26-HOBO SH16
28-HOBO SH14
27-HOBO SH09
69-HOBO SH20
65-HOBO SH02
68-HOBO SH19

54-HOBO SH23
55-HOBO SH17
56- HOBO SH25
58-noHOBO
57-HOBO SH26
48-noHOBO

Propylene Release Location for Experiment 2

Experiments 1 and 2: Sat 5/18/02- Sun 5/19/02
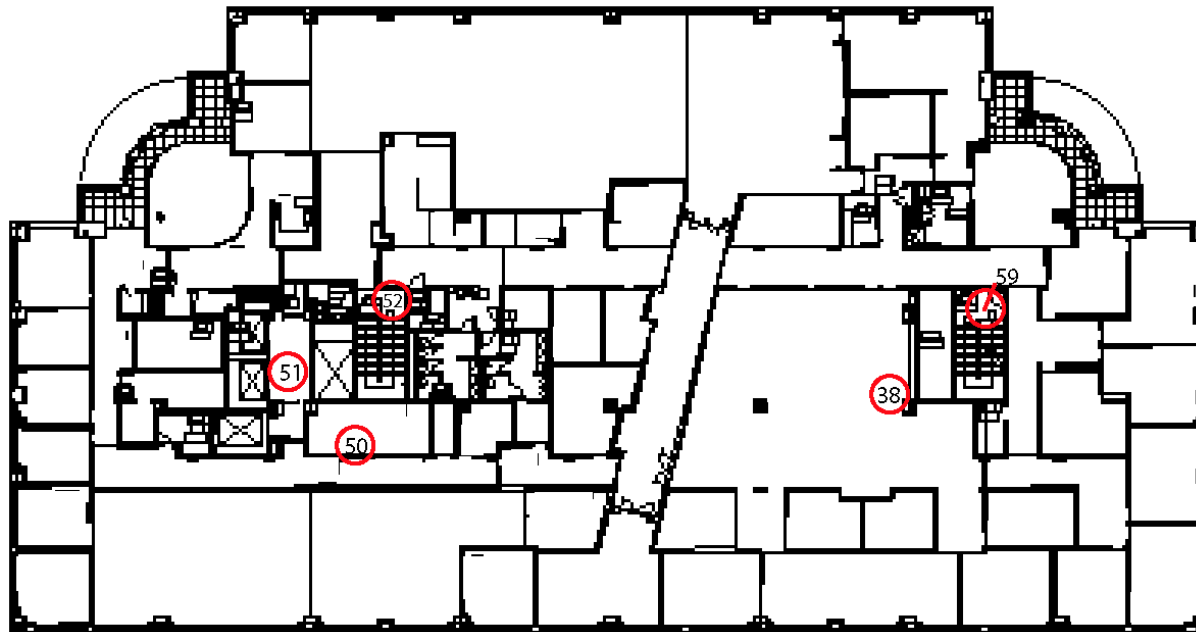
6th Floor

38-HOBO SH24
59-HOBO SH06
50-HOBO SH03 (for 1bc2a, DPID#53 for 1a)
51-HOBO SH18
52-HOBO SH01
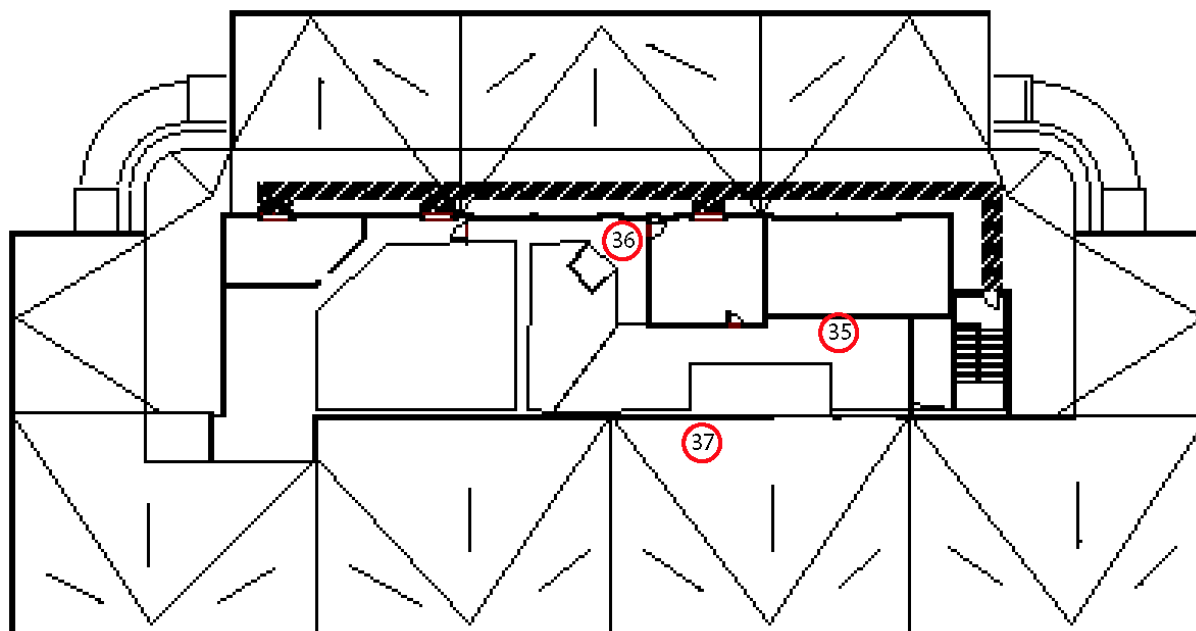
Experiments 1 and 2: Sat 5/18/02- Sun 5/19/02

36-on outside air intake screen, edge penthouse
35-in airstream from 1-4 return
37-in Millvan east inlet

Penthouse

A-10

Experiments 3-6: Fri 5/24/02- Mon 5/27/02

58

27

56

65

28

40

54

45

68

69

61
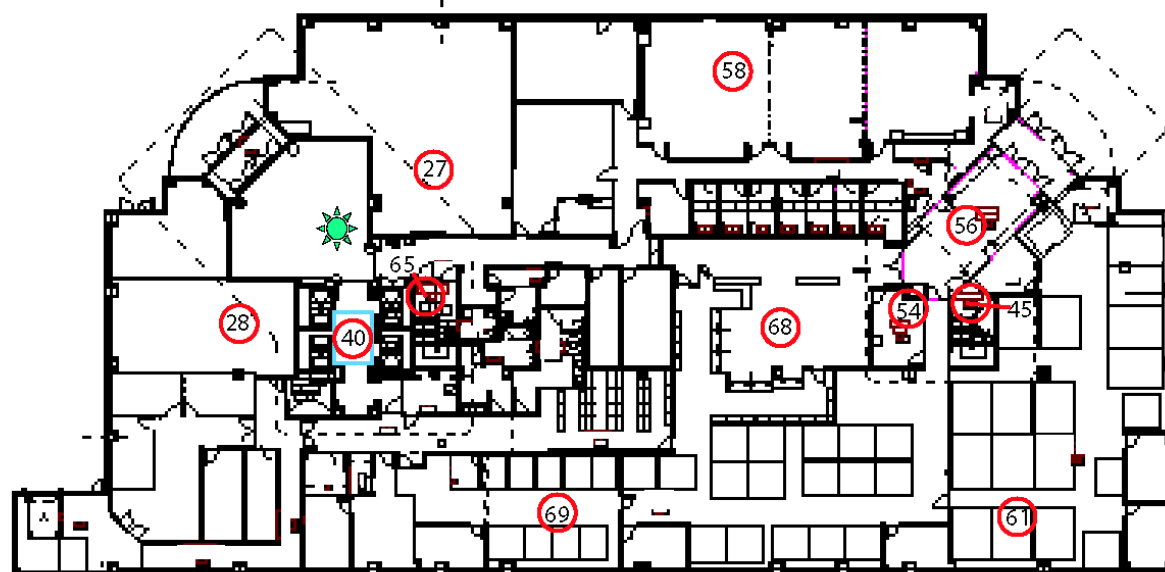
40- HOBO SH04, Blue box 9(run 6)
28- HOBO SH14
27- HOBO SH09
65- HOBO SH02
58- no HOBO

1st Floor

56- HOBO SH25
45- HOBO SH15
54- HOBO SH23
68- HOBO SH19
61- HOBO SH08
69- HOBO SH20

Propylene Release Location for
Experiments 3-6

Experiments 3-6: Fri 5/24/02- Mon 5/27/02

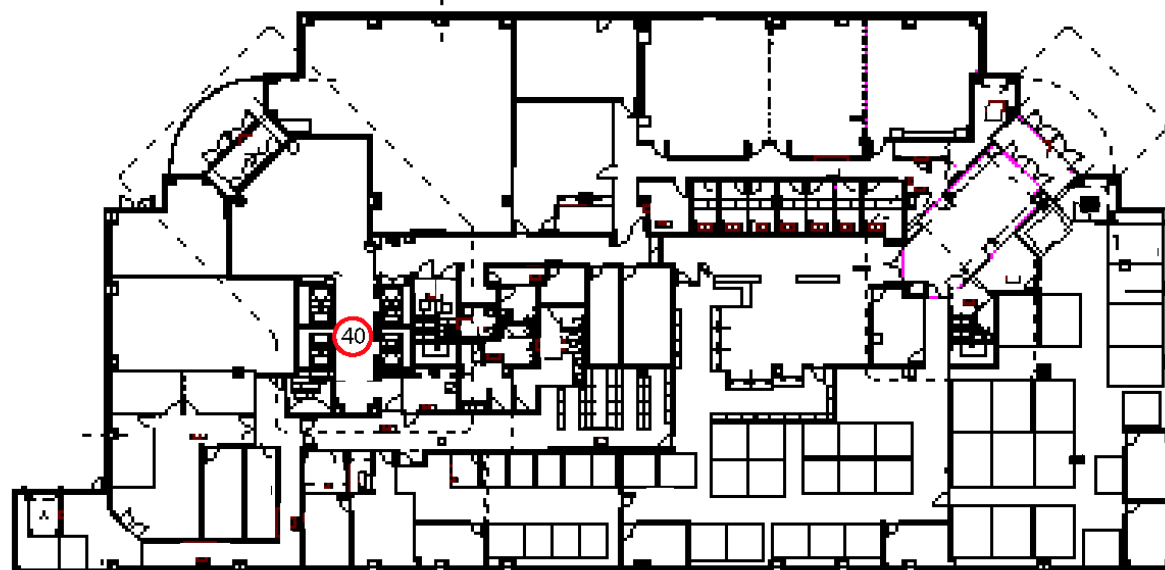
38

39
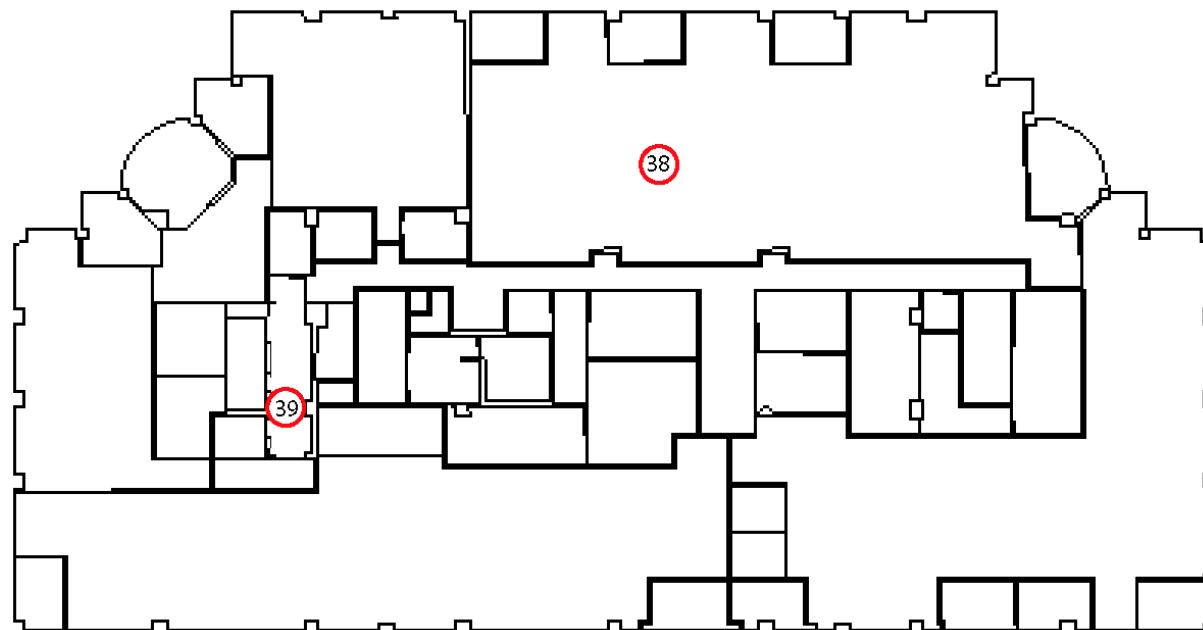
39-HOBO SH11
38-HOBO SH24

2nd Floor

A-12

Experiments 3-6: Fri 5/24/02- Mon 5/27/02

46-HOBO SH22
42-HOBO SH05 (ceiling plenum)

3rd Floor

Experiments 3-6: Fri 5/24/02- Mon 5/27/02
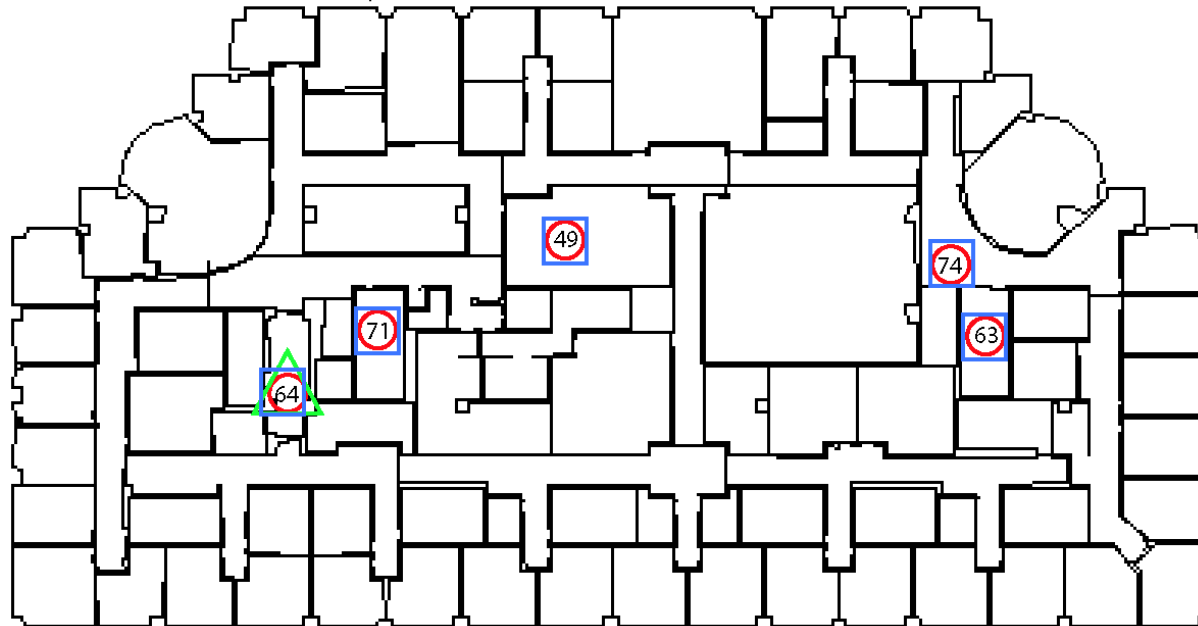
49- HOBO SH13, Blue box 04
63- HOBO SH12, Blue box 43
64-HOBO SH21, Blue box 12(run 6), MiranC
71- HOBO SH10, Blue box 23(run 6)
74- HOBO SH07, (ceiling return), Blue box 06(runs 3 and 4)

4th Floor

Experiments 3-6: Fri 5/24/02- Mon 5/27/02
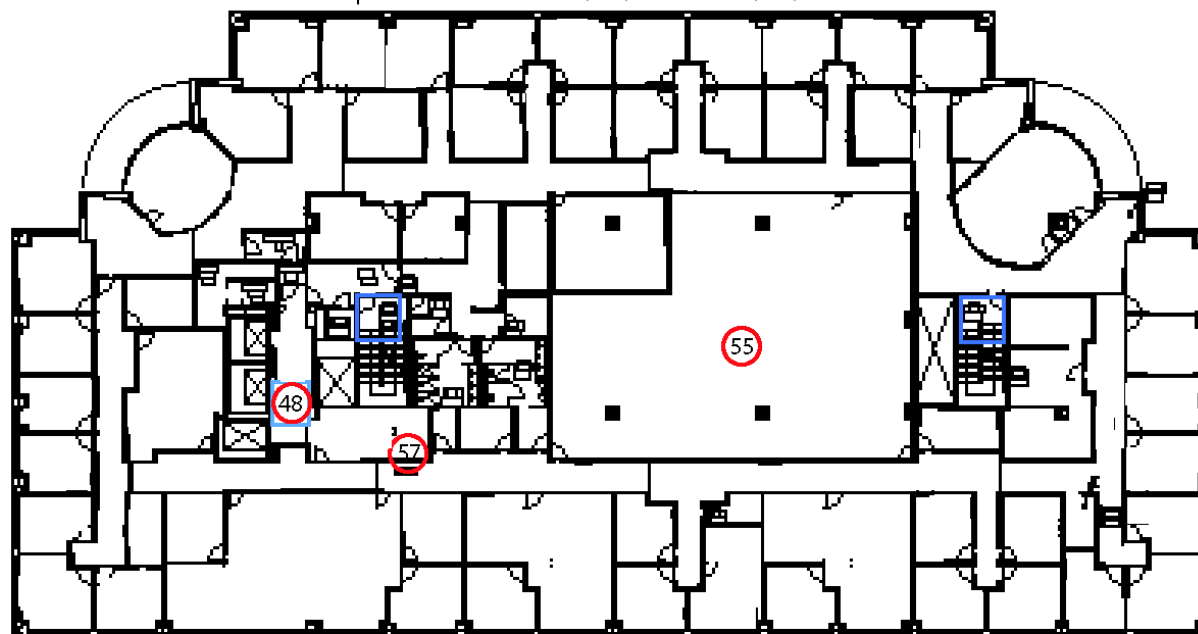
55-HOBO SH17
57-HOBO SH26, Blue box 9(runs 3 and 4)
48-noHOBO, Blue box 23(runs 3 and 4)

5th Floor

5th West Stairwell-Blue box 29(run 6)
5th East Stairwell-Blue box 17(run 6)

Experiments 3-6: Fri 5/24/02- Mon 5/27/02
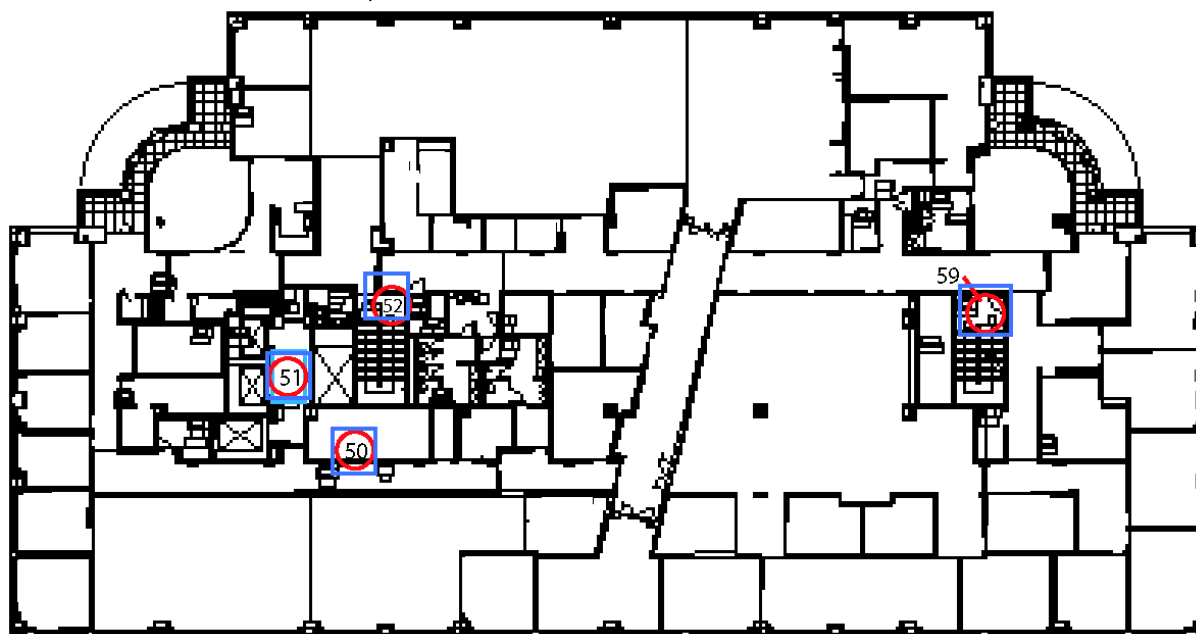
50-HOBO SH03, Blue box 34
51-HOBO SH18, Blue box 39
52-HOBO SH01, Blue box 17(runs3 and 4)
59-HOBO SH06, Blue box 12(runs 3 and 4)

6th Floor

Experiments 3-6: Fri 5/24/02- Mon 5/27/02
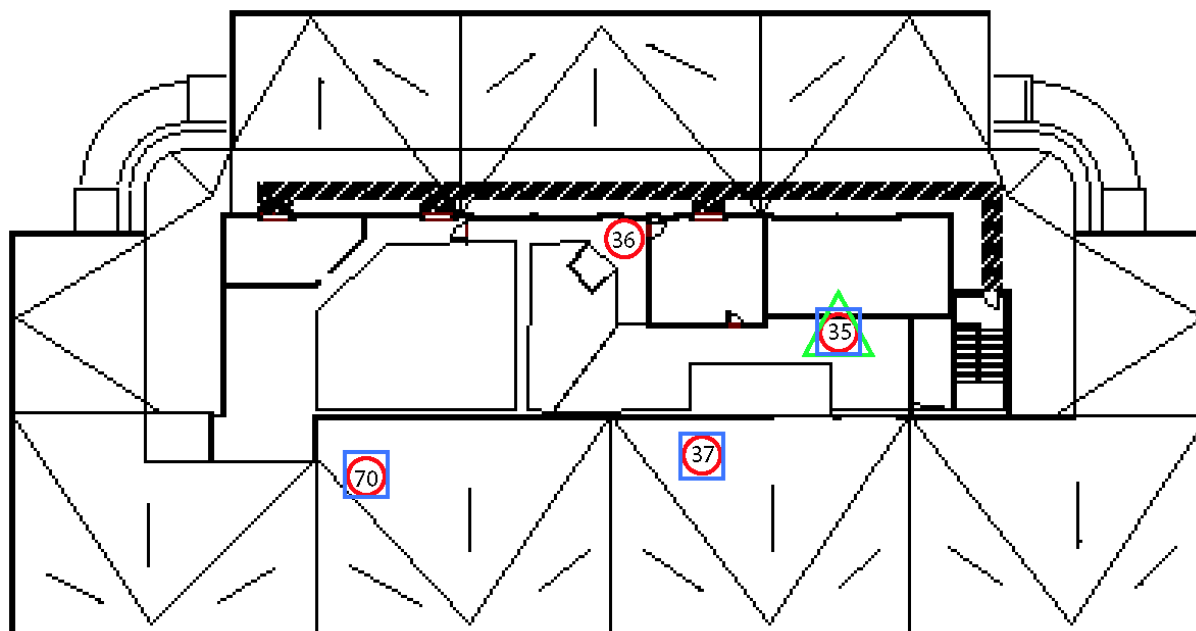
35-in airstream from 1-4 return, Blue box 6 (run 6) Miran D(runs 3, 4, and 5)
36-on outside air intake screen, edge penthouse

Penthouse

37-in Milvan east inlet, Blue box 25(runs 3 and 4)
70-elevator exhaust, Blue box 29(runs 3 and 4)
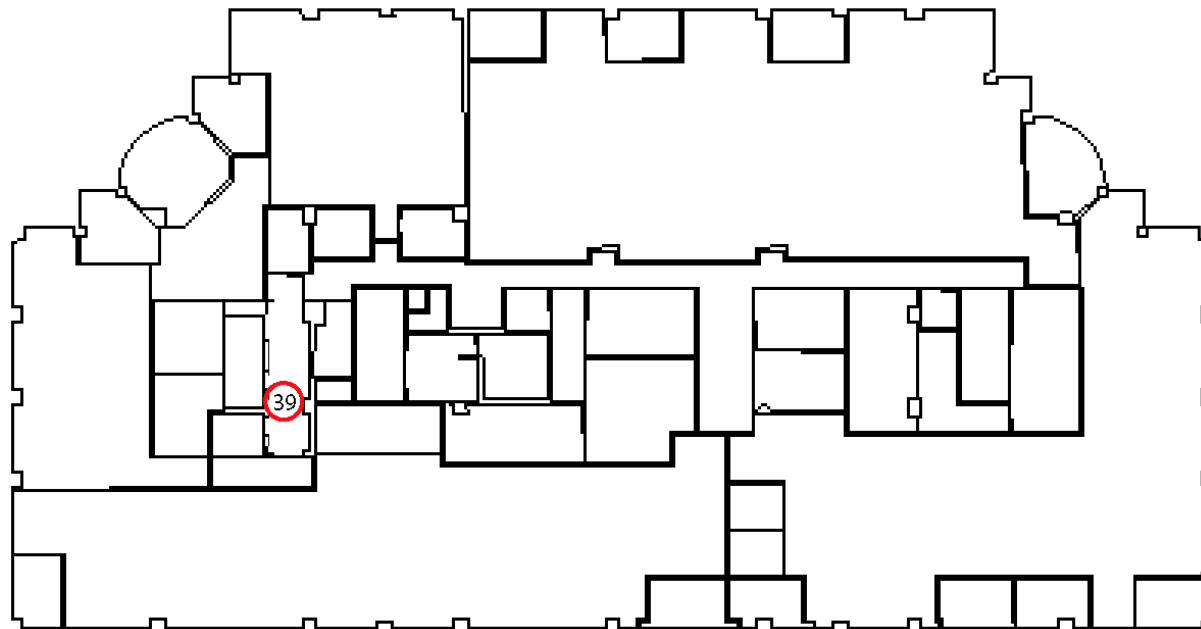
Experiments 7-10: Sat 6/1/02- Sun 6/2/02

40
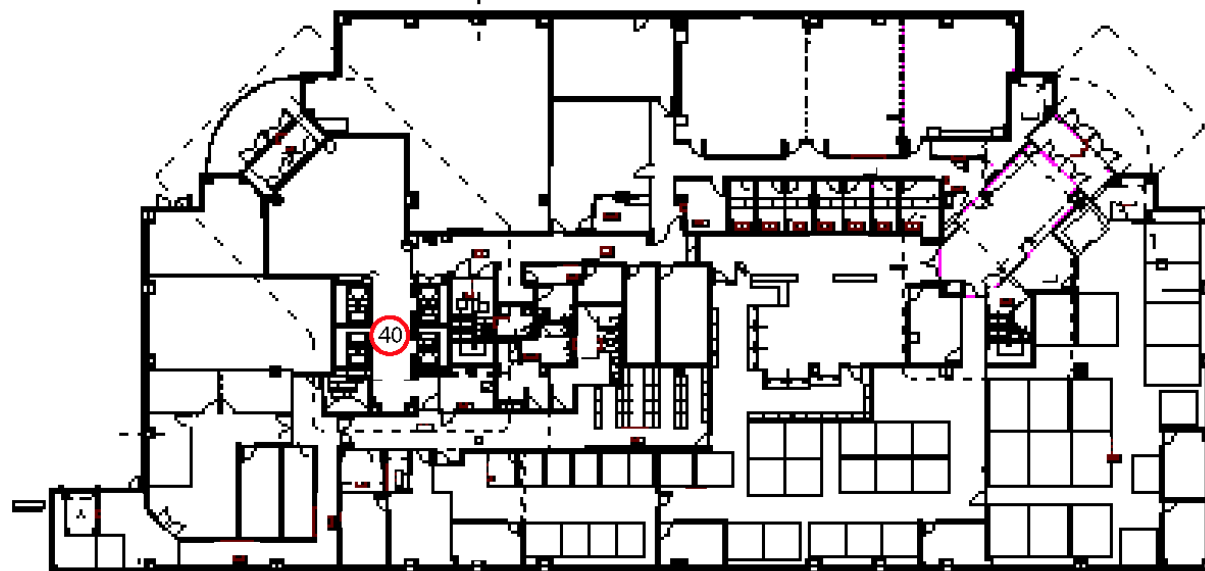
40- HOBO SH04

1st Floor
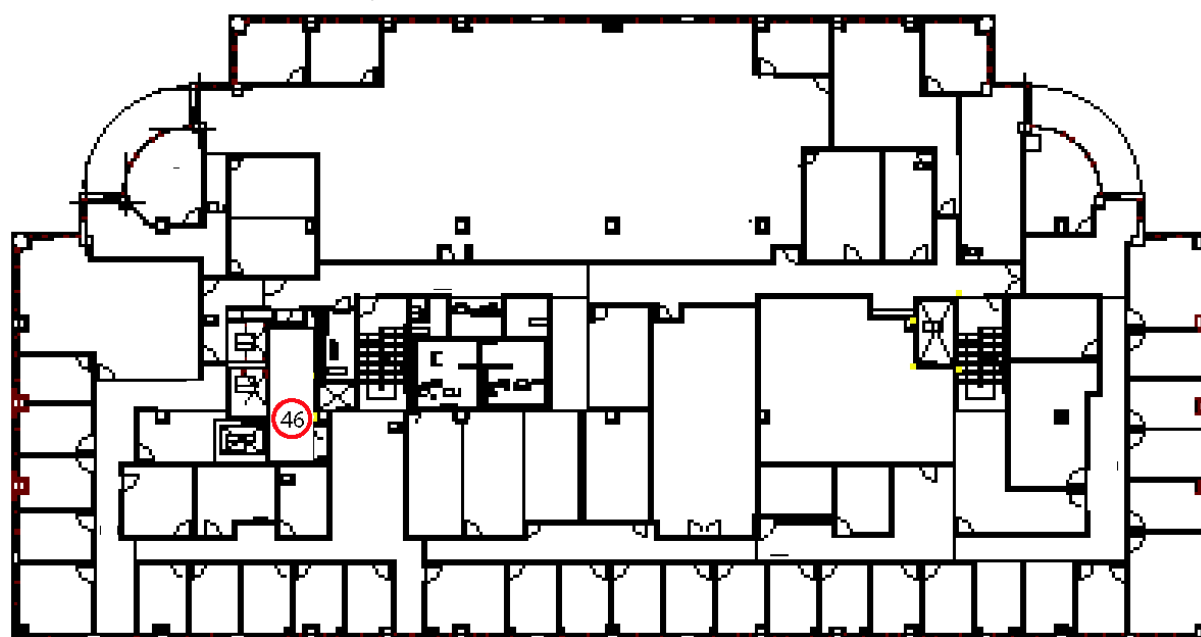
Experiments 7-10: Sat 6/1/02- Sun 6/2/02

39-HOBO SH11

2nd Floor
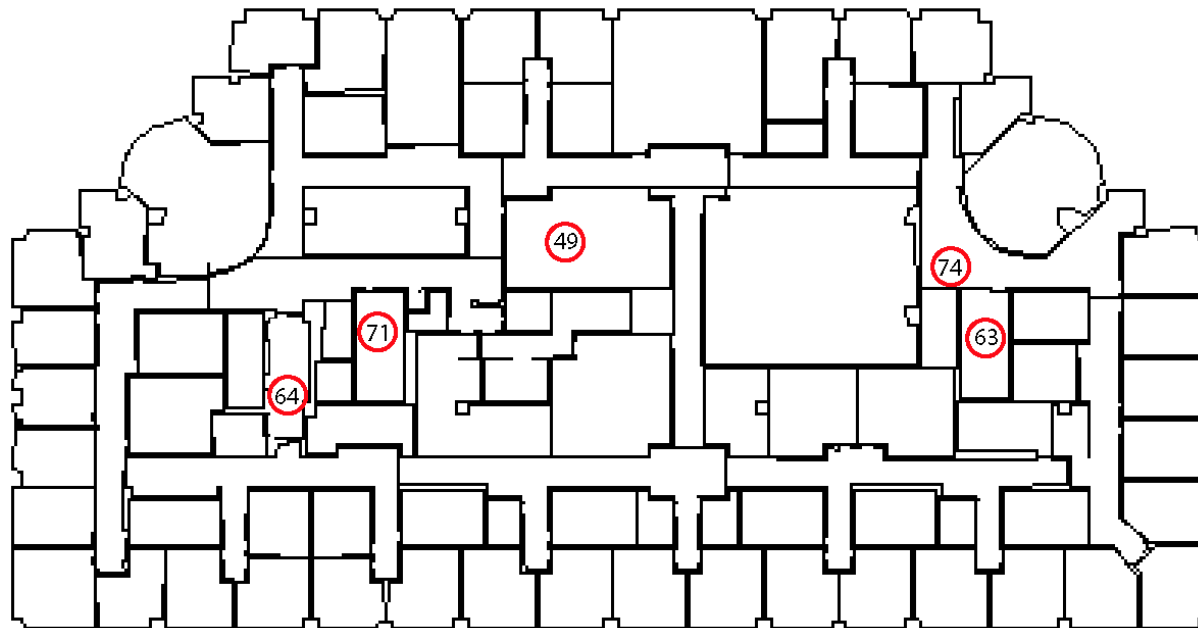
Experiments 7-10: Sat 6/1/02– Sun 6/2/02
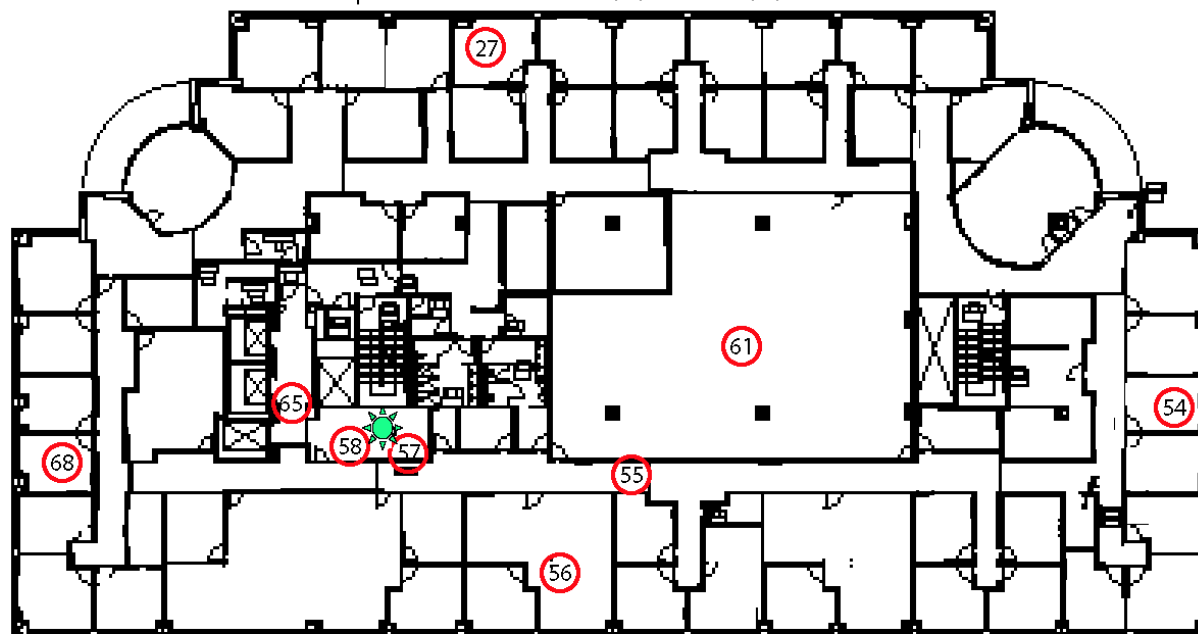

46-HOBO SH22

3rd Floor

Experiments 7-10: Sat 6/1/02- Sun 6/2/02

64-HOBO SH21
71- HOBO SH10
49- HOBO SH13
74- HOBO SH07 (ceiling return)
63- HOBO SH12

4th Floor

Experiment 7 : Sat 6/1/02
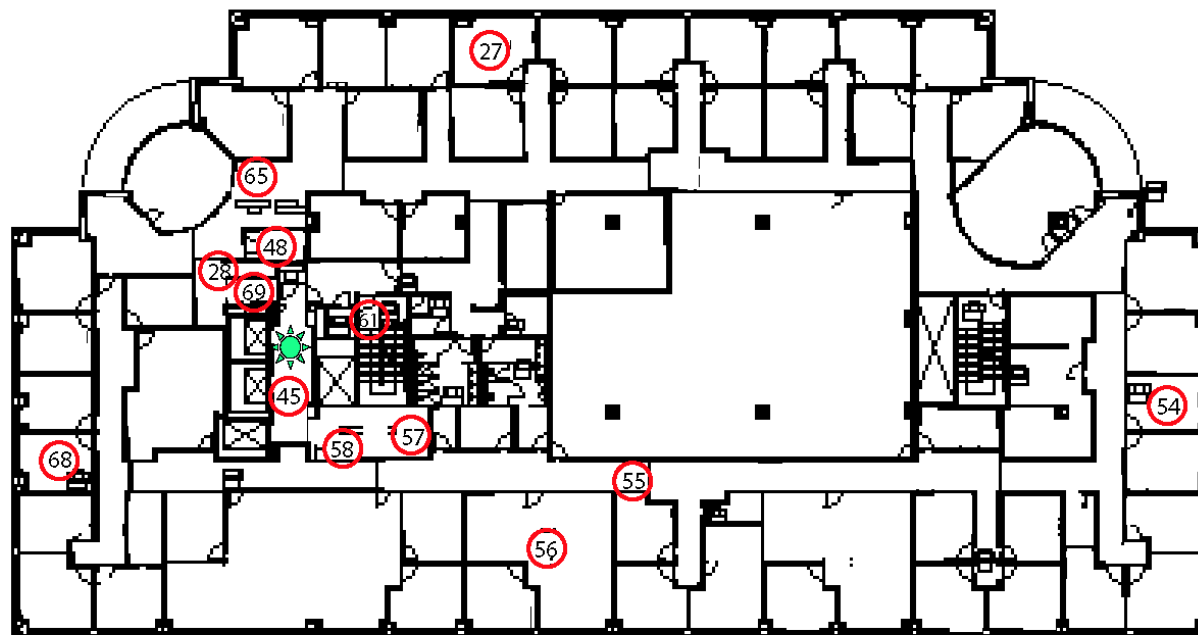
27-HOBO SH09
28-HOBO SH14
69-HOBO SH20
48-noHOBO
65-HOBO SH02
68-HOBO SH19

54-HOBO SH23
55-HOBO SH17
56- HOBO SH25
58-noHOBO
57-HOBO SH26
45-noHOBO
61-HOBO SH08

5th Floor

Propylene Release Location for Experiment 7

Experiments 8-10: Sat 6/1/02- Sun 6/2/02

27-HOBO SH09
28-HOBO SH14
69-HOBO SH20
48-noHOBO
65-HOBO SH02
68-HOBO SH19

54-HOBO SH23
55-HOBO SH17
56- HOBO SH25
58-noHOBO
57-HOBO SH26
45-noHOBO
61-HOBO SH08

5th Floor

⊛ Propylene Release Location for Experiment 7

⊛ Propylene Release Location for Experiment 10

Experiments 7-10: Sat 6/1/02– Sun 6/2/02
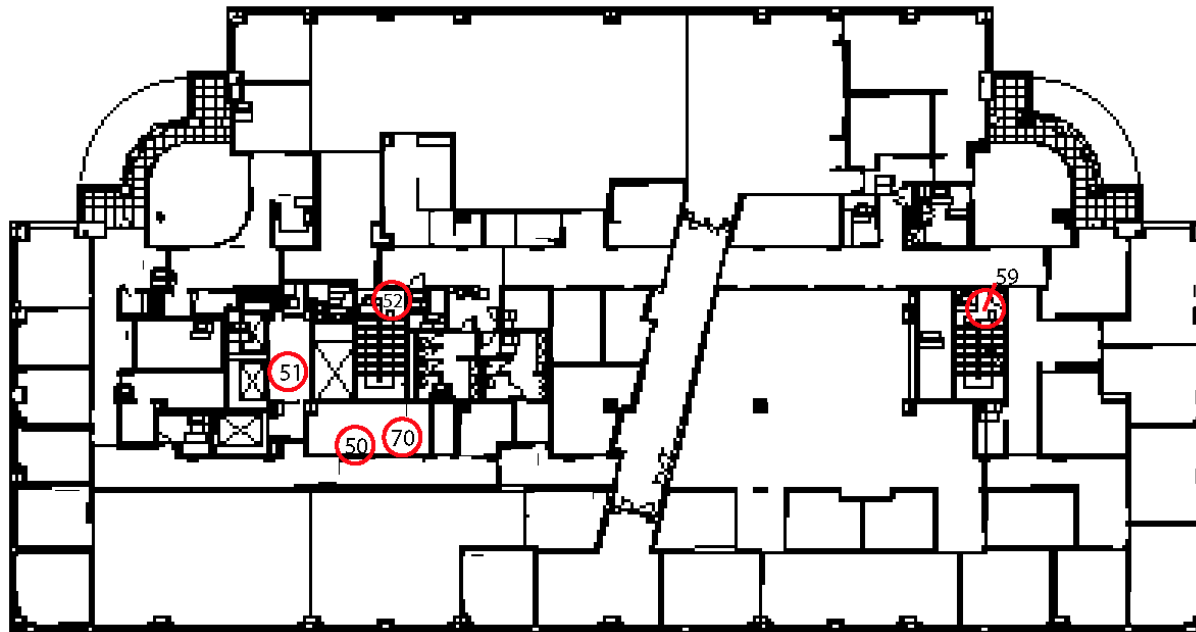
59-HOBO SH06
70-No HOBO
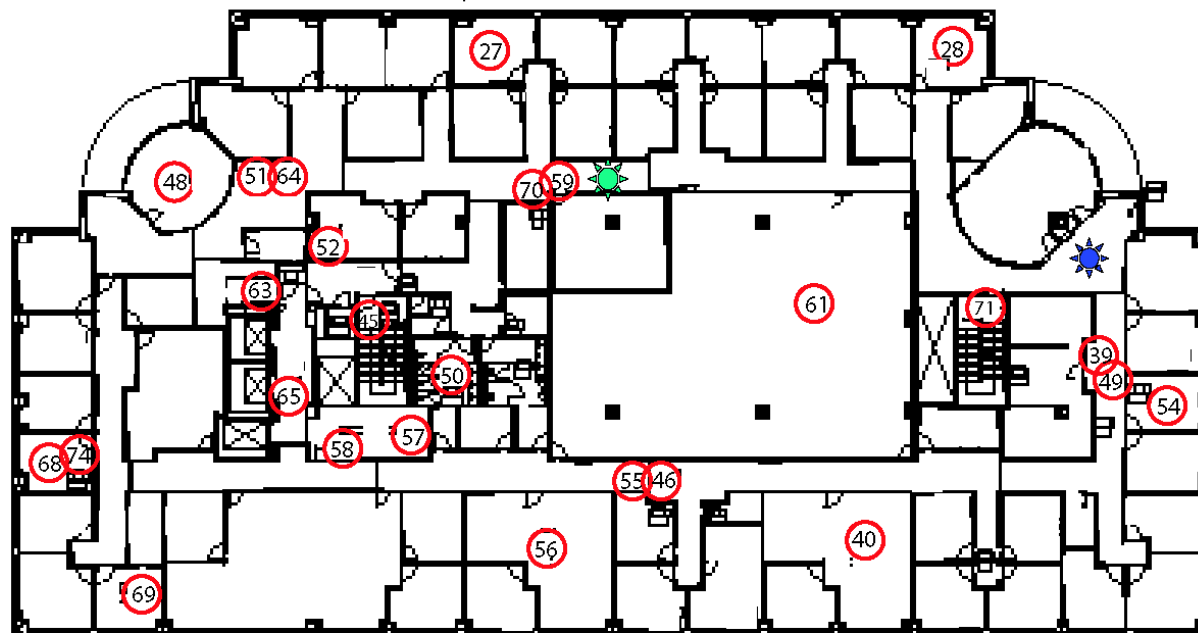50-HOBO SH03
51-HOBO SH18
52-HOBO SH01

6th Floor

Experiments 7-10: Sat 6/1/02- Sun 6/2/02

36-on outside air intake screen, edge penthouse
35-in airstream from 1-4 return
37-in Milvan east inlet
38-bathroom exhaust
42-elevator exhaust

Penthouse

A-25

Experiments 11-14: Fri 6/7/02- Sat 6/8/02

40- HOBO SH04

1st Floor

Experiments 11-14: Fri 6/7/02- Sat 6/8/02

39-HOBO SH11

2nd Floor

Experiments 11-14: Fri 6/7/02– Sat 6/8/02

46-HOBO SH22

3rd Floor

Experiments 11-14: Fri 6/7/02- Sat 6/8/02

64-HOBO SH21
71- HOBO SH10
49- HOBO SH13
74- HOBO SH07(ceiling return)
63- HOBO SH12

4th Floor

Experiments 11-14: Fri 6/7/02- Sat 6/8/02

61-HOBO SH08   54-HOBO SH23
27-HOBO SH09   55-HOBO SH17
68-HOBO SH19   56- HOBO SH25
                 58-no HOBO
                 57-HOBO SH26
                 65-HOBO SH02

5th Floor

Propylene Release Location for
Experiments 13 and 14
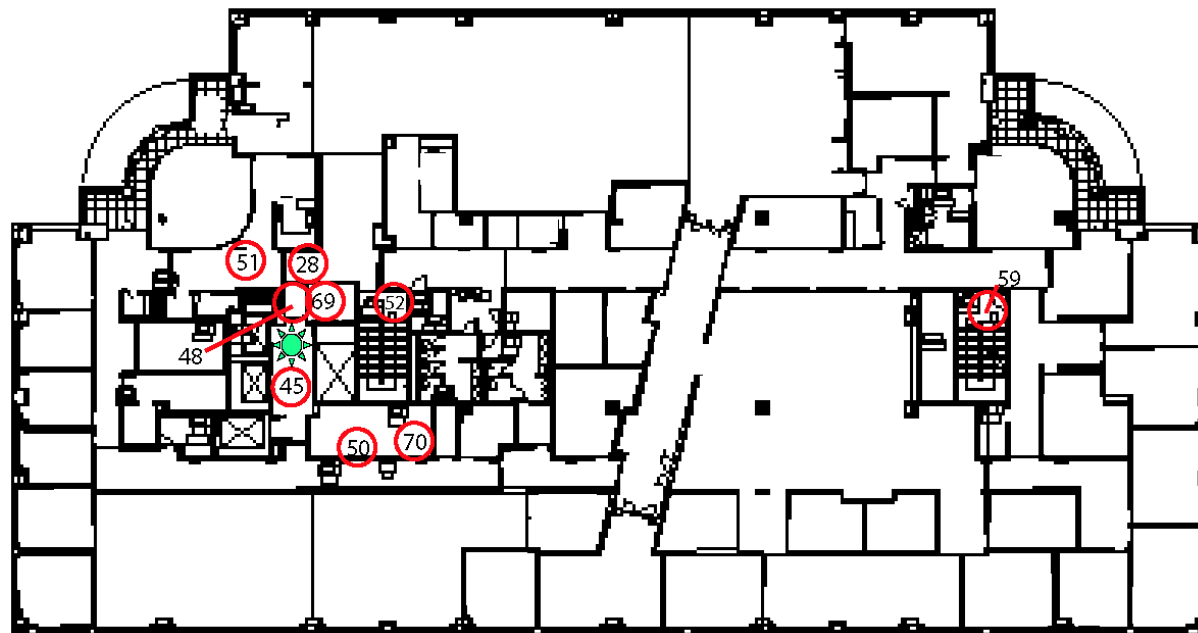
6th Floor

59-HOBO SH06
70-no HOBO
50-HOBO SH03
45-no HOBO
51-HOBO SH18

28-HOBO SH14
48-no HOBO
69-HOBO SH20 failed
52-HOBO SH01

Propylene Release Location for
Experiments 11 and 12

Experiments 11-14: Fri 6/7/02- Sat 6/8/02
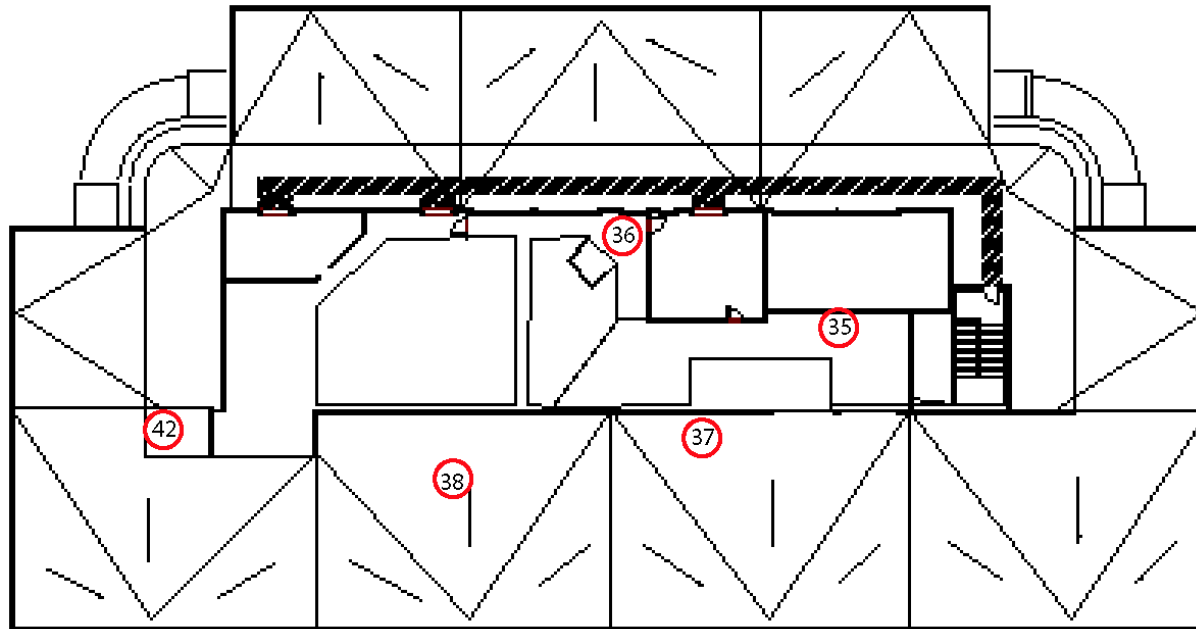
36-on outside air intake screen, edge penthouse
35-in airstream from 1-4 return
37-in Milvan east inlet
38-bathroom exhaust
42-elevator exhaust

Penthouse

Experiments 15 and 16: Sun 6/9/02

5th Floor

27-HOBO SH09
28-HOBO SH14
48-no HOBO
51-HOBO SH18 (plenum)
64-HOBO SH21
70-no HOBO (plenum)
59-HOBO SH06
52-HOBO SH01
61-HOBO SH08

71-HOBO SH10
39-HOBO SH11 (plenum)
49-HOBO SH13
54-HOBO SH23
40-HOBO SH04
55-HOBO SH17
46-HOBO SH22 (plenum)

56- HOBO SH25
58-no HOBO
57-HOBO SH26
50-HOBO SH03
45-no HOBO
63-HOBO SH12
65-no HOBO
68-HOBO SH19
74-HOBO SH07 (plenum)
69-HOBO SH20

Propylene Release Location Exp 15

Propylene Release Location Exp 16

Experiments 15 and 16: Sun 6/9/02
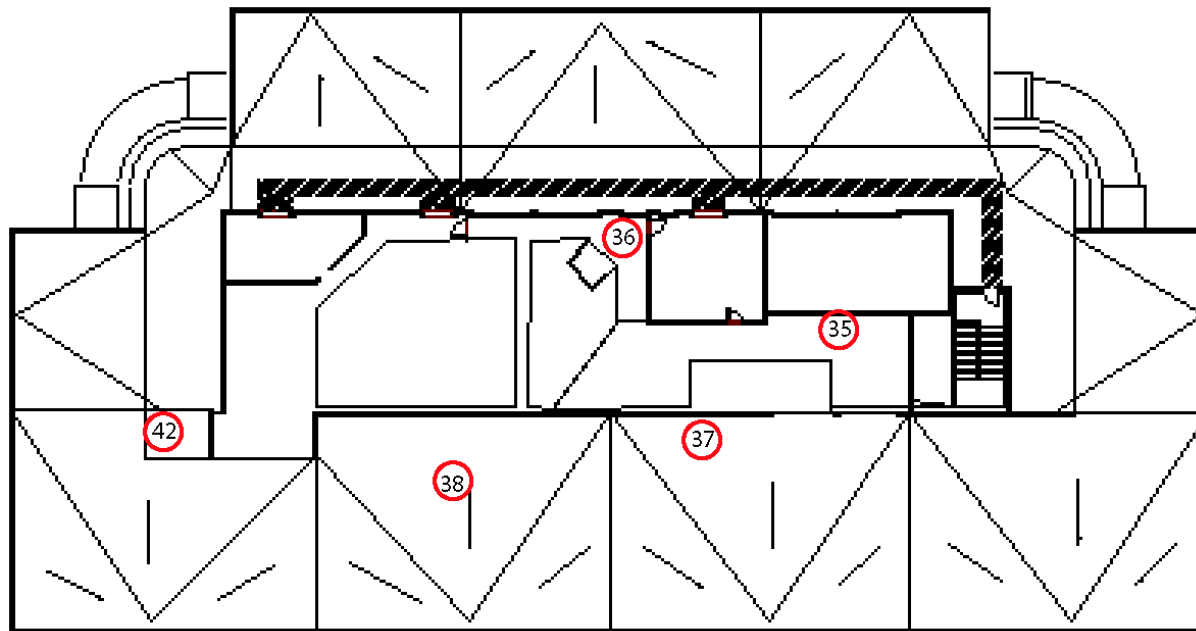
36-on outside air intake screen, edge penthouse
35-in airstream from 1-4 return
37-in Millvan east inlet
38-bathroom exhaust
42-elevator exhaust

Penthouse

Appendix B: Folder and file names for all data files and instrument location maps

I. Salt Lake City 2002 Data Files
- **a. Differential Pressure Data**
  - **i. week 1**
    1. dp_1lobby_17to19May02
    2. dp_6office_19May02
    3. dp_6hall_18to19May02
  - **ii. week 2**
    1. dp_1lobby_25to27May02
    2. dp_6office_25to27May02
    3. dp_6hall_24to27May02
  - **iii. week 3**
    1. dp_1lobby_31Mayto02Jun02
    2. dp_6office_31Mayto02Jun02
    3. dp_6hall_31Mayto02Jun02
  - **iv. week 4**
    1. dp_1lobby_07to09Jun02
    2. dp_6office_07to09Jun02
    3. dp_6hall_07to09Jun02
    4. dp_6decon_08Jun02
- **b. Interior Temperature Data**
  - **i. week 1 and 2**
    1. sh01-08, sh10-19, sh21-26 (24 total)
  - **ii. week 3**
    1. sh01-19, sh21-26 (26 total)
  - **iii. week 4**
    1. sh01-19, sh21-26 (26 total)
- **c. Outdoor Meteorological Data**
    1. met_airport_21Mayto19Jun02
    2. met_shproof_17to19May02
    3. met_shproof_24to27May02
    4. met_shproof_31Mayto10Jun02
- **d. Propylene PID Data**
    1. PID_data_description_readme
  - **ii. week 1**
    1. shp_week1_1min
    2. shp_week1_1sec
    3. shpx1b_50Hz
    4. shpx1c_50Hz
    5. shpx1d_50Hz
    6. shpx2_50Hz
  - **iii. week 2**
    1. shp_week2_1min
    2. shp_week2_1sec
    3. shpx3A_50Hz
    4. shpx3B_50Hz
    5. shpx4A_50Hz